DESIGN OF AN EXPERIMENTAL MINE SIMULATOR FOR THE DEVELOPMENT OF A PROCEDURE FOR UTILIZATION OF MULTIPLE TRACER GASES IN UNDERGROUND MINES

by

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Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science

In

Mining and Minerals Engineering

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April 26, 2011

Blacksburg, VA

Keywords: mine ventilation, tracer gas, mine scale model

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Abstract

An experimental mine simulator was constructed which will be used to conduct tracer gas experiments in the laboratory. The test apparatus simulates a mine in a tabular deposit and is modular and simple and can be easily rearranged to represent a variety of mine geometries. The apparatus is appropriate for the use of tracer gases by being both airtight and open-circuit (exhausting to the atmosphere) and by maintaining turbulent flow throughout the model, ensuring the tracer gas is fully dispersed.

The model features ports for injection and sampling of tracer gases, which represent boreholes present in an actual mine. The model is designed, in part, for the practice of tracer gas release and sampling methods in the laboratory. Valves on the apparatus represent ventilation controls, such as stoppings or regulators, or changing resistances in a mine, such an increase in resistance due to a roof fall or a decrease in resistance due to stoppings being destroyed. The relative resistances of airways can be changed by changing the status of the valves to represent different states of the ventilation controls.

The mine simulator should serve as a tool for identifying and investigating novel tracer gases, developing a procedure for performing ventilation surveys using multiple tracer gases, and eventually developing a method for remotely inferring ventilation changes using tracer gases.

ACKNOWLEDGEMENTS

I would first like to thank my advisor, Dr. Kray Luxbacher, for her patience and guidance throughout my graduate studies. I would also like to thank Dr. Saad Ragab and Dr. Erik Westman for their input and support.

Second, I would like to thank Jim Waddell for the hours of help in construction in the laboratory and Robert Bratton for his technical guidance in selecting instrumentation.

I would also like to thank the lovely and always helpful department administrative staff, Carol Trutt, Gwen Davis, and Kathryn Dew for signing forms and ordering all my parts and always greeting me with a smile.

Additionally, I want to thank my fellow graduate students Charles Schlosser, Edmund Jong, Rosemary Patterson, and Guang Xu for their assistance in tasks related to the construction of the experimental apparatus.

Finally, I would like to acknowledge the National Institute for Occupational Safety and Health (NIOSH), especially our program coordinator Dr. Gerrit Goodman, for providing the primary monetary support for this project.

This publication was developed under Contract No. 200-2009-31933, awarded by the National Institute for Occupational Safety and Health (NIOSH). The findings and conclusions in this report are those of the authors and do not reflect the official policies of the Department of Health and Human Services; nor does mention of trade names, commercial practices, or organizations imply endorsement by the U.S. Government.

All photographs were taken by the author, 2011.

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1. INTRODUCTION

With a continued demand for mined resources, underground mines continue to become more complex as a result of the increasing difficulty in extracting dwindling and ever less-accessible reserves. As the complexity of mine geometries increases, coupled with increasing concern over methane control and dilution in the wake of recent explosions, continually rising energy costs and the fairly recent introduction of stricter legislation limiting miners' exposure to pollutants such as diesel particulate matter (DPM), the demand for more complex and reliable mine ventilation is further increased. As mine ventilation networks become more complex, traditional methods of ventilation surveys become increasingly cumbersome or, in some cases, ineffective at solving ventilation problems.

Chemical tracers have been used abundantly to describe fluid flows in both the natural and man-made environment. Some fields in which chemical tracers have been used successfully include hydrology, pollution dispersion, urban meteorology, industrial hygiene, building ventilation and mine ventilation. A tracer gas is a gas which can be diffused in relatively small proportions in a volume of air and which is detectable in trace amounts at another point or points downstream. Depending on the particular tracer gas used, the robustness of the experimental method, and the sensitivity and precision of the instruments, a tracer gas can be detected and quantified in concentrations ranging from parts-per-billion (ppb) to parts-per-trillion (ppt).

The primary qualities of a useful tracer gas in a ventilation network are the ability to diffuse in the airstream (such that the fully diffused gas downstream represents the flow of the airstream), chemical stability, and the ability to be detected and quantified in low concentrations. These entail that the chemical is gaseous at the atmospheric conditions in the ventilation network, the tracer gas does not undergo any chemical changes or interact with other chemicals in the atmosphere and that the tracer gas is not naturally occurring (lest slight concentration changes be minor fluctuations of the natural concentration). For mine ventilation, other qualities determine the usefulness of a tracer gas. A successful tracer gas for mine ventilation should be relatively inexpensive, easily obtainable, not harmful to miners and not radioactive[1].

The concept of using tracer gases has been applied in mine ventilation surveys for over 60 years. Tracer gases have allowed for the solution of increasingly complex problems in mine ventilation, previously unsolvable via conventional ventilation survey methods. The only standard tracer gas used in ventilation surveys, sulfur hexafluoride (SF_6), meets all the above criteria. SF_6 has been used profusely in mine ventilation to solve complex problems; however it has been demonstrated both in civil and mine ventilation that a method for using several tracer gases simultaneously can allow for far more complex surveys to be conducted in less time. In order for a tracer gas to be successful for use in a complex survey procedure with SF_6 it must also be detectable using the same method as SF_6, namely using a gas chromatograph (GC) with an electron capture detector (ECD).

The long-term goals of this research include identifying and investigating novel tracer gases, developing a procedure for performing ventilation surveys using multiple tracer gases, and describing a post-disaster mine response based in part on the multiple tracer gas method. The candidate gases identified will be evaluated based on chemical properties which are favorable to performance as tracer gases in mine ventilation surveys. In contribution to that research effort, a laboratory-scale mine simulator was constructed which is to be used as an experimental apparatus for tests performed with tracer gases. Simplified tracer gas ventilation surveys will be conducted in the apparatus, which will allow for the evaluation of the gases both as tracers (the ability to detect them at trace concentrations) and their ability to be used in conjunction with one another in ventilation surveys (the ability to separate the gases from one another and from air and other common mine gases). The location of a test apparatus near the GC in the laboratory

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[1] Radioactive tracers have been used previously in both building and mine ventilation and can be detectable at much lower concentrations. The researchers in this study decided to preclude radioactive tracers on the basis that the increased training, handling and storage requirements make nonradioactive chemical tracers more desirable for practical application mine ventilation. Additionally, the test methods for “conventional” chemical tracers are more thoroughly developed and accepted in the mining industry.

allows researchers to easily perform routine sampling and analysis procedures representative of those made in mine conditions and to practice the complex techniques necessary for tracer gas analysis. The system also allows for changes to the ventilation circuit, so that the validity of using tracer gases to characterize damage to the controls can be tested.

2. LITERATURE REVIEW

2.1. TRACER GASES

Gaseous chemical tracers have been used in many disciplines to better understand fluid flow. Examples of applications of chemical tracers in fluids, both liquid and gaseous, are plentiful in science and engineering. As the application of chemical tracers is a mature field, focus will be placed primarily on the use of gaseous tracer as applied to ventilation studies.

2.1.1. PROPERTIES OF TRACER GASES

In order for tracer gases to be useful, they must have suitable chemical and physical properties for use as chemical tracers. A gas which is useful as a chemical tracer should be

- detectable at low concentrations
- safe
- acceptable to miners (not radioactive)
- odorless
- chemically and thermally stable
- not naturally occurring in the environment
- able to diffuse into mine air
- easy to handle and store, and
- relatively inexpensive [1,2].

Some of these criteria define chemical properties of tracer gases, such as the ability to be detectable at low concentrations, generally via gas chromatography (GC) [3,4]. Other criteria define physical properties of the gases like the ability to diffuse into mine air, which is related to the molecular weight or, for volatile organic vapors, their partial pressure in air at mine conditions. Some of these properties are more complicated functions of chemical properties, like the cost or the ease of handling and storage.

Tracer gas surveys often view parts of the ventilation system as a "black box" in which chemical tracer input and output are measured to determine information about the volumetric flow rates, splits, and recirculation within the system. In order for tracer gas concentrations to be reflective of air flows, the gas must be shown to fully disperse in the mine air to achieve a uniform concentration throughout the air volume. The gas must also transport through the ventilation system without being chemically changed or becoming trapped in the system. The gas must remain chemically stable at mine atmospheric conditions and not significantly react with nor adsorb onto any materials in the mine.

The process dominating gas-solid surficial interaction is *adsorption*. Adsorption is a process by which gas (or vapor/liquid) molecules adhere to a solid surface without chemically combining with the solid [5-7]. Adsorption is observed to take place between every known chemical species of gas and any solid surface at some temperature and pressure conditions [7]. Adsorption can be divided into two main types, depending on the process by which the gas molecules are adhering to the surface. The process resulting in the weakest bonds is *physical adsorption* or *physisorption*, in which the adsorption is also reversible (via a process called *desorption*) [5]. The process resulting in an irreversible (via physical processes) process, in which the gas molecules combine physically with the solid surface, is called *chemical adsorption* or *chemisorption* [5,6]. In chemisorption, there is initially an electron exchange between the gas molecule and solid surface which precedes the chemical reaction [5]. Chemically stable tracer compounds interact with mine surfaces through physical adsorption, since they should not react chemically with any substances in the mine.

2.1.2. SULFUR HEXAFLUORIDE AS A TRACER GAS IN THE MINING INDUSTRY

Prior to its application in the mining industry, SF_6 was previously used as a tracer gas in environmental and meteorological studies using the tracer to study the dispersion of airborne pollutants [8-10]. Tracer gases were also used in the heating, ventilation and air conditioning (HVAC) industry to measure the ventilation efficiency of large buildings [11,12]. It was previously shown by Lester and Greenberg that SF_6 was nontoxic, an important property of a chemical tracer [13]. The case for SF_6 as a tracer gas was also built when two studies demonstrated that SF_6 could be detected at concentrations as low as 10^{-5} ppm using GC with an electron capture detector (ECD) [3,4].

Tracer gases were first applied in the mining industry in 1958 when nitrous oxide was used as a tracer to determine airflow in headings [14]. The first use of SF_6 as a tracer gas by the mining industry occurred in 1972, when SF_6 was introduced into Appalachian oil and gas wells prior to the halting of oil production and subsequent mining through the wells [15]. SF_6 was injected into the production wells prior to them being plugged and during the period through which the wells were being mined, gas samples were taken from the mine exhaust air and analyzed for SF_6 as an indicator of leakage from the wells.

The first application of SF_6 as a tracer gas mine ventilation aid occurred in 1974 when the U.S. Bureau of Mines reported on studies performed using SF_6 [1]. Thimons et al. cite several studies performed in three mines in which the tracer gas method was applied successfully using SF_6: in a coal mine, an underground limestone mine and a western vein-type metal mine. Two additional reports followed that year from the Bureau of Mines, adding to the already broad scope of proven and potential applications of SF_6 in mine ventilation analysis. In one report, Thimons and Kissell described the use of SF_6 in quantifying recirculation, checking for air leakage, tracing lost air, and measuring the transit time of air through a mine [2]. In another report, Kissell and Bielicki demonstrated that SF_6 could be used in a model mine to quantify the ventilation air held up in eddies at the working face [16]. Findings from these Bureau of Mines studies effectively laid the groundwork for the application of tracer gases in mine ventilation, increasingly referred to in literature as the "tracer gas method." These studies also demonstrated the appropriateness of SF_6 as a tracer gas by showing that when fully diffused, it follows the path of the airstream and that SF_6 does not adsorb to coal or sandstone surfaces nor is it removed from ventilation air by mine air cooling plants. They established standard release and sampling procedures, described the analysis of the gas concentrations using solid-gas chromatography and documented useful equations.

In 1975 Kissell and Bielicki used SF_6 as a tracer gas in a full-scale laboratory experiment to demonstrate the recirculation in a coal mine working face due to dust scrubbers on continuous miners [17]. The study showed that though dust scrubbers did cause some recirculation of air, it was not a major contributing factor to the buildup of methane at the working face. The following year, Vinson and Kissell reported on three ventilation studies conducted by the Bureau of Mines using SF_6 as a tracer gas [18]. These three studies used SF_6 to investigate air leakage in a sealed area, the ventilation efficiency of a bleeder system, and leakage across stoppings in parallel intake airways. Following the analysis of the results of the individual studies, Vinson and Kissell concluded that the application of SF_6 should be considered to help "solve ventilation problems that do not respond to conventional methods of ventilation analysis."

Matta, Maksimovic, and Kissell used SF_6 in a tracer decay test as a new method for quantifying leakages through permanent stoppings [19]. Using the tracer gas method, leakages through stoppings as low as 15 cfm could be measured, whereas using the Bureau of Mines' previously established window brattice method, the maximum measureable leakage rate was approximately 300 cfm [20]. Another application for the tracer gas method was established in the evaluation of the ventilation efficiency of auxiliary ventilation [21].

The role of SF_6 as a tracer gas in the mining industry was solidified by applications in several areas, as documented by a summary of Bureau of Mines studies [22]. SF_6 was used in coal mining to determine face ventilation efficiency [23], evaluate gob ventilation in three coal mines [24], investigate the effectiveness of a new continuous miner ventilation system for very deep cuts [25] and to determine the integrity of escapeways during a fire [26]. SF_6 was applied in a silica mill to evaluate the effectiveness of silica-bagging machine exhaust hood enclosures [27]. SF_6 saw use in uranium mines in evaluating the ventilation of an in-stope uranium flood leaching operation [28]. Finally, SF_6 was used in a large-opening oil-shale pilot mine to determine and compare the ventilation efficiencies of alternative auxiliary ventilation methods and to evaluate the effects of blast pressures on large stoppings [29-31].

2.1.3. Multiple tracer gases for more complex ventilation problems

The selection of cited studies prior serves to prove that the tracer gas technique is a useful tool in solving complex ventilation problems. Airflows in complex networks are often difficult to trace and/or quantify; both of these problems can be solved by the use of tracer gases. Further research in both HVAC and mine ventilation has demonstrated that surveys of significantly complex ventilation networks can benefit from the use of multiple tracer gases simultaneously.

A considerable amount of work has been done in the field of HVAC using multiple tracer gases to characterize airflow. In 1973 Foord and Lidwell used multiple tracer gases to describe the complex airflows in large nonresidential buildings such as hospitals [12]. Fisk et al. used SF_6 along with five other halocarbons in a system to describe the overall airflow pattern in a large building [32]. The system described by Fisk et al. featured six independent automated gas release devices and independent automated gas samplers which capture a volume of air at a regular interval (15 minutes in their study). Lagus et al. used multiple tracer gases in a study of the ventilation at a nuclear power facility in Arizona [33]. Lagus et al. applied SF_6 along with bromotrifluoromethane ($CBrF_3$) and perfluorodimethlcyclohexane (PDCH). In a later series of articles, also compiled into a more in-depth publication, Grot and Lagus review the various tracer gas procedures for use in industrial hygiene, including a lists of equipment and a list of electronegative halocarbons which make effective tracer gases [34-38].

After developing their own sampling and release systems for SF_6, Kennedy et al. at the Cape Breton Coal Research Laboratory (CBCRL) recognized a need for multiple tracer gases for complex ventilation surveys. Kennedy et al. conducted a series of experiments with SF_6, Freon-12 (CCl_2F_2) and Freon-13B1 (CBr_3F), all of which are detectable using a gas chromatograph with ECD and all of which are of similar molecular weight [39,40]. Kennedy et al. used a GC with two columns for their chromatography, in which the SF_6 and Freon-13B1 were split from the Freon-12 and sent into separate columns within the same GC oven [41]. Kennedy et al. described potential problems with Freon-12 including sample loss due to adsorption in the syringe and analysis interference possibly caused by a hydrocarbon propellant in spray paint underground [39].

Both Fisk et al. and Lagus et al. encountered problems using some halocarbons as tracer gases since many halocarbons are commonly-used refrigerants or other products and may be present in the gaseous background [32,33]. Kennedy et al. also described difficulty with the use of some Freons, as some possibly existed in the mine air background [39]. Both Kennedy et al. and Lagus et al. examined the use of Freons as tracer gases and both were able to successfully use Freon-13B1 (bromotrifluoromethane/$CBrF_3$) as a tracer gas alongside SF_6, although Kennedy chose to analyze the Freon on a separate column from SF_6 [33,39].

Following the initial 1987 studies using multiple tracer gases conducted by the Cape Breton Coal Research Laboratory, there have been no major developments in mining regarding the use of multiple tracer gases. Klinowski and Kennedy of the CBCRL reiterated the efficiency gained by using multiple tracer gases in a single survey in a summary of tracer gas techniques [42]. Numerous studies in mine ventilation applying the tracer gas technique used only SF_6, including applications in dust control in mineral processing [43,44], auxiliary ventilation [45], controlled recirculation [46,47], face ventilation in continuous mining [48-51], gob ventilation [52-55], testing leakage across stoppings [56], turbulence and diffusion modeling [57], narrow-vein shrinkage stope ventilation [58]. One study used only helium as a tracer gas to investigate overburden fracturing above longwall gobs [59]. Though their usefulness was well-demonstrated and they have seen considerable use in other areas such as building ventilation, it is far from common practice to simultaneously use multiple tracer gases in mine ventilation studies.

2.2. FLUID DYNAMICS

A mine ventilation network is a complex system of fluid (ventilation air) in motion, though it can be compared to – and often significantly simplified as – a pipe or duct network. Individual airways (branches) can be described using the Bernoulli energy equation and the Atkinson equation, while the whole network can be represented as a network of resistances and solved via application of Kirchhoff's laws [60,61]. As with any physical system, the physical laws governing the system offer a means of qualitative solution of the system variables. Table 2-1 lists common variables used in mine ventilation along with their units [60].

TABLE 2-1: SELECTED VARIABLES USED IN MINE VENTILATION

Physical Quantity	Variable	English Units	SI Units
Pressure	P	psi (lb/in^2)	(k)Pa
Pressure head* (Head loss)	H	in. w.g.	mm w.g.
Velocity	V	fpm (ft/min)	m/s
Quantity (volumetric flow rate)	Q	cfm (ft^3/min)	m^3/s
Length, Diameter, Perimeter	L, D, O	ft	m
(Cross-sectional) Area	A	ft^2	m^2
Density	ρ	lb_m/ft^3	kg/m^3
Specific weight**	w	lb/ft^3	N/m^3
Acceleration of gravity	g	ft/sec^2	m/s^2
Atkinson friction factor	K	$lb{\cdot}min^2/ft^4$	kg/m^4

*Pressure head is often used in place of pressure, or interchangeably.
**Specific weight is more common than density in the English unit system.

2.2.1. IMPORTANT RELATIONSHIPS IN MINE VENTILATION

Through the application of fluid dynamics equations, a number of important physical and thermodynamic relationships have been adopted for use in mine ventilation. Each of these equations is derived from the governing equations of fluid mechanics: the continuity equation, the conservation of momentum, and the conservation of energy.

Relevant equations presented here are Eq. (2.1) the quantity-velocity relationship, Eq. (2.2) the Bernoulli energy equation, Eq. (2.3) the Bernoulli equation in its more common form (with terms expressed as heads rather than specific energies), Eq. (2.4) the Atkinson equation, Eq. (2.6) the definition of total head, and Eq. (2.7) the relationship between velocity and velocity head [60]. All variables are as defined in Table 2-1 unless otherwise stated. Coefficients in Eq. (2.5) and Eq. (2.8) are derived for use with variables in English units, e.g. velocity in fpm; these are the common form these equations take in mine ventilation in the U.S.

Quantity-velocity relationship

$$\mathrm{Q} = V_{avg}\mathrm{A} \qquad \text{Eq. (2.1)}$$

Bernoulli energy equation, as specific energy and as fluid heads

$$\frac{P_1}{w} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{w} + \frac{V_2^2}{2g} + Z_2 + H_{loss} \qquad \text{Eq. (2.2)}$$

$$H_{s_1} + H_{v_1} + H_{z_1} = H_{s_2} + H_{v_2} + H_{z_2} + H_{loss} \qquad \text{Eq. (2.3)}$$

where Z is elevation, in ft (m)
H_s is static head, in ft (m) of fluid
H_v is velocity head, in ft (m) of fluid
H_z is elevation head, in ft (m) of fluid

Atkinson equation for friction loss (and as typically used in English units)

$$H_{friction} = \frac{\mathrm{KOL}Q^2}{A^3} = RQ^2 \qquad \text{Eq. (2.4)}$$

$$H_{friction} = \frac{\mathrm{KOL}Q^2}{5.2A^3} \qquad \text{Eq. (2.5)}$$

where K is the Atkinson friction factor, in lb·min^2/ft^4 (kg/m^4)
O is the perimeter of the airway, in ft (m)
L is the length of the airway, in ft (m)
Q is the quantity, in ft^3/min (m^3/s)
A is the cross-sectional area of the airway, in ft^2 (m^2)
R is the total airway resistance, in min^2/ft^6 (N·s^2/m^8)

Total, static and velocity head relationship

$$H_{total} = H_{static} + H_{velocity} \qquad \text{Eq. (2.6)}$$

Velocity-velocity head relationship (and as typically used in English units)

$$H_{velocity} = \frac{V^2}{2\text{g}} \qquad \text{Eq. (2.7)}$$

$$H_{velocity} = w\left(\frac{V}{1098}\right)^2 \qquad \text{Eq. (2.8)}$$

2.2.2. TURBULENT FLOW DEVELOPMENT

When a body of fluid moves linearly, as in a pipe, duct, or channel (henceforth: conduit), it can be observed to behave in one of three distinct patterns, or *flow regimes*, dependent on the fluid velocity, density, viscosity, and a characteristic length in the fluid system (generally the diameter of the conduit for conduit flow) [62,63]. This term, known as the Reynolds number, is presented as Eq. (2.9) [60,61,64]

$$\text{Re} = \frac{\rho \text{VL}}{\mu} = \frac{\text{VL}}{\nu} \qquad \text{Eq. (2.9)}$$

where V is fluid velocity, in ft/sec (m/s)
L is characteristic length, in ft (m)
μ is dynamic viscosity, in lb·sec/ft^2 (N·s/m^2)
ν is kinematic viscosity, in ft^2/sec (m^2/s).

In conduit flow, the characteristic length is often the diameter (if the conduit is round) or the hydraulic diameter, D_H, for any shaped conduit. The hydraulic diameter is defined such that the hydraulic diameter equals the diameter for a circular conduit [61,64] and is given by

$$D_H = \frac{4A}{O} = \frac{4\left(\frac{\pi D^2}{4}\right)}{(\pi D)} = D \qquad \text{Eq. (2.10)}$$

where D_H is the hydraulic diameter (of any shape conduit), in ft (m)
A is the cross-sectional area of the conduit, in ft^2 (m^2)
O is the perimeter of the conduit, in ft (m)
D is the diameter (for round conduits), in ft (m).

Generally, flows for which $\mathrm{Re} < 2000$ can be described as moving in sheets (laminae), so the flow regime is considered *laminar* [60,61,64]. Flows for which $\mathrm{Re} > 4000$ behave irregularly and exhibit a great deal of mixing; this flow regime is described as *turbulent*. Flows between these two regimes, for which $2000 < \mathrm{Re} < 4000$, exhibit elements of both laminar and turbulent flow (partially developed turbulence, limited eddies); this third flow regime is appropriately referred to as *transitional*, as the flow appears to be in transition from laminar to turbulent.

When a fluid flows past a solid surface, some of the fluid is slowed by friction with the surface in an effect called *friction drag* [64]. Since some of the fluid has slowed, the adjacent fluid experiences a shear stress, the magnitude of which increases with the viscosity of the fluid (a property of the fluid determining the resistance to shear stress) [64]. This shear stress has the effect of slowing an even thicker layer of fluid, and thus the *boundary layer* develops. The boundary layer is the layer of fluid in which viscous forces have an effect on fluid flow [64]. When a fluid flows within a conduit, a velocity profile taken across the diameter of the conduit reveals a parabolic velocity distribution, with the highest translational fluid velocity (velocity in flow direction) in the center of the conduit and lower velocities near the walls of the conduit. This velocity gradient near the walls is a result of the viscous boundary layer. Conduit flow (also channel flow, pipe flow) is the condition in which the boundary layer encompasses the conduit radius. The parabolic velocity profile generally remains the same throughout a conduit, except near the inlet and where the flow is affected by other changes to the conduit such as contractions or expansions, bends, valves, splits, etc. [64].

When a fluid enters a conduit, it does not immediately demonstrate the velocity profile defining conduit flow. The region through which fluid travels immediately following the entrance is called the *entrance region*, during which the viscous boundary layer progressively thickens until it encompasses the conduit radius [64]. The distance in a conduit before which the conduit flow velocity profile is fully-developed is referred to as the *entrance length*, L_e [64]. Reynolds noted that the entrance length is a function of conduit diameter and estimated that turbulent flow, as estimated by the development of eddies in a dye stream injected into the conduit, developed approximately 30 diameters into a conduit [61-63]. Lien et al, in a recent study of estimates for entrance length, found literature estimating entrance lengths ranging widely between less than 30 to greater than 200 and recommends conservatively assuming an entrance length of 150 diameters [65]. The entrance length for a conduit in which flow is turbulent, as defined by the Reynolds number, is much shorter than for a conduit in which flow is laminar. Young et al. present the following equation for the entrance length for turbulent flow as a function of Re and conduit diameter [64]

$$L_e = 4.4(\mathrm{Re})^{1/6} D \qquad \text{Eq. (2.11)}$$

where L_e is entrance length, in ft (m)
D is conduit (hydraulic) diameter, in ft (m)
Re is Reynolds number, dimensionless.

2.2.3. Velocity/quantity measurement using Pitot-static tubes

Several options are available for anemometry, including plate orifices, vane anemometers, Pitot-static tubes, hot-wire anemometers, laser-Doppler systems, and ultrasonic anemometers. A Pitot tube is a metal tube whose open end (usually rounded to be more aerodynamic) is parallel to the flow direction and whose other end is connected to a pressure-measuring device such as a manometer or electronic pressure transducer. A Pitot tube is usually bent at 90° to protrude into an airstream or duct from within a housing or outside the duct. A Pitot-static tube, also called a Prandtl tube, consists of two concentric tubes, one of which measures the stagnation (total) pressure from the sensing tip, and the other of which measures the static pressure of the moving fluid through static pressure taps (holes exposed perpendicular to the flow) behind the sensing end. A diagram of a Pitot-static tube is displayed as Figure 2.1 [66]. A Pitot-static tube is generally more useful than a Pitot tube since the difference between total and static pressure, velocity head, can be measured with one instrument. Although technically incorrect, the term Pitot tube is often used to describe the more common Pitot-static tube.

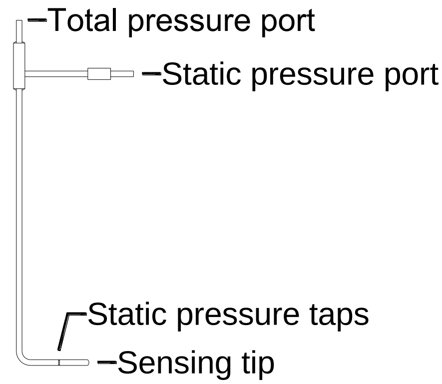

FIGURE 2.1. GEOMETRY OF A PITOT-STATIC TUBE

Assuming the standard Pitot-static tube design and an air velocity much lower than the speed of sound (a low Mach-number flow), the air velocity can be determined using Eq. (2.12) [66]:

$$\mathrm{V} = 44.72136\sqrt{\frac{H_v}{\rho}} \qquad \text{Eq. (2.12)}$$

where V is air velocity, in m/s
H_v is velocity head (total pressure – static pressure), in kPa
ρ is air density, in kg/m^3.

The air density, corrected for water vapor content, can be calculated by Eq. (2.13) and Eq. (2.14) [66]:

$$\rho = 3.4834\ \frac{P_{bar}}{T} \cdot \left[1 - \left(\frac{0.3783 \cdot \frac{RH}{100} \cdot P_S}{P_{bar}}\right)\right] \qquad \text{Eq. (2.13)}$$

$$P_s = 1.7526 \times 10^8 \cdot e^{-5315.56/T} \qquad \text{Eq. (2.14)}$$

where ρ is air density, in kg/m^3
P_{bar} is barometric pressure, in kPa
T is absolute temperature, in K
RH is relative humidity, in %
P_S is the partial pressure of water vapor at T, in kPa.

2.3. Scale models

Scale modeling has proven useful in numerous fields of science, engineering, and design to make predictions about a structure or system. Architects use scale models to design buildings, including the reflection and diffusion of light from various surfaces. Naval architects have long used water basins to study the performance characteristics of watercraft. Similarly, wind tunnels are used extensively to study the performance of automobiles and all manner of air- and spacecraft. Hydrology, geophysics and meteorology are also fields which have benefitted greatly from the application of scale models. Nearly every engineering discipline concerned with physical systems has made extensive use of scale models for studying very large or very small structures or systems [64,67]. Scale models are "experimental models structured to mirror the true physical behavior of an original phenomenon, or a prototype" [67]. The system represented by the model is called the *prototype*. The model is usually much smaller than the prototype so as to be easier to handle, be more easily accessible or controllable, cost less to build and operate, use fewer materials, and/or be generally simpler to understand [64,67].

With the rapid increase of the computational abilities and availability of computers, numerical models are increasingly reinforcing and replacing physical scale models [68]. Better understanding of physical phenomena and the development of novel numerical methods for the solution of systems of partial differential equations (PDEs) have contributed to the development of increasingly robust numerical models of physical problems. A very successful numerical model for the analysis of dynamic fluid systems is Computational Fluid Dynamics (CFD). Over the past few decades, CFD simulation has become much cheaper while wind tunnel testing has become more expensive, making CFD increasingly instrumental in the field of fluid dynamics [68].

Although numerical modeling tools such as CFD have made great advances over the past few decades, they still have not entirely replaced physical experimentation. CFD, as with all numerical solution methods, has its inherent drawbacks. A CFD simulation is only as accurate as the information used to create the model. Complex behavior such as eddies and chemically reactive flows rely heavily on submodels based on generalized assumptions [68]. Physical scale models are still necessary to provide the proper input, especially boundary conditions, into numerical models. A CFD model can achieve a high degree of precision, but with inaccurate input data may be unrepresentative of the actual physical system.

2.3.1. MODELING THEORY: SIMILITUDE

When creating scale models of systems containing fluid flow, it is important to be certain that the measurements made on the model system represent behavior of the prototype system; to achieve this goal, the concept of *similitude* is applied [64]. Most relevant forces in a system of dynamic fluids often do not scale linearly with length, making the responsible use of any scale model difficult without attention not only to geometric similarity (length ratios), but also to kinematic similarity (velocity and acceleration ratios) and kinetic similarity (force/moment ratios) [64,67,69]. In model theory, the Buckingham pi theorem is applied in order to maintain similitude between the model and prototype. Pi theorem involves applying dimensional analysis to derive unique dimensionless groups (ratios) of variables which are used to maintain similarity between the model and prototype, referred to as *pi terms*. Pi terms are constructed from variables which determine the system behavior (e.g., pressure, velocity, length, viscosity and density) and from the physical laws relating them (e.g. velocity = length/time, pressure = force/area, kinetic energy = ½ × mass × velocity^2) [67,69]. Many useful pi terms in fluid dynamics are force ratios such as those shown in Table 2-2 [64].

TABLE 2-2: SOME COMMON DIMENSIONLESS GROUPS IN FLUID MECHANICS

Dimensionless Group	Name	Interpretation (Index of Force Ratio Indicated)	Types of Applications
$\frac{\rho V L}{\mu}$	Reynolds number, Re	$\frac{\text{inertia force}}{\text{viscous force}}$	Generally of importance in all types of fluid dynamics problems
$\frac{V}{\sqrt{gL}}$	Froude number, Fr	$\frac{\text{inertia force}}{\text{gravitational force}}$	Flow with a free surface
$\frac{p}{\rho V^2}$	Euler number, Eu	$\frac{\text{pressure force}}{\text{inertia force}}$	Problems in which pressure or pressure differences are of interest
$\frac{V}{c}$	Mach number, Ma	$\frac{\text{inertia force}}{\text{compressibility force}}$	Flows in which the compressibility of the fluid is important

Variables: Acceleration of gravity, g; Characteristic length, L; Density, ρ; Pressure, p; Speed of sound, c; Velocity, V; Viscosity, μ

Models which maintain similitude (geometric, kinematic and kinetic similarity) by having all pi terms equal between model and prototype (i.e., $\Pi_{1M} = \Pi_{1P}$, $\Pi_{2M} = \Pi_{2P}$, etc.) are referred to as *true models* [64]. Models which do not meet all the similarity requirements (e.g., $\Pi_{1M} = \Pi_{1P}$, $\Pi_{2M} \neq \Pi_{2P}$) are referred to as *distorted models*. Often in order to maintain similitude between the model and prototype, the working fluid (specifically, the density and viscosity of the working fluid) must be changed in the model, e.g. by representing air in the prototype system with water in the model. Distorted models, while if applied improperly can yield misleading information about the behavior of the prototype, are often necessary. Such cases could arise when maintaining perfect similitude is impossible or impractical, such as when a fluid with the required viscosity or density is unreasonable to use or nonexistent. In such cases where a distorted model is used, care must be taken in extrapolating model behavior to make assumptions about the prototype.

2.3.2. LOW-SPEED WIND TUNNEL DESIGN

Experiments performed with scale models require a testing environment in which the fluid flow can be controlled and the performance of the model can be tested. In fields requiring the use of aerodynamics such as aeronautics and automobile design, the working fluid is usually standard air and the apparatus to perform experiments with moving air is called a wind tunnel. All modern wind tunnels share four common features: an area for experimentation in which the flow parameters can be sufficiently controlled called the *test section* or *working section*, an effuser prior to the test section, a diffuser after the test section, and a source for air motion (often a fan) [70,71]. The effuser is usually a contraction which serves to increase the air velocity and usually contains screens to condition the flow (for more uniform flow). The diffuser serves to efficiently convert velocity energy back into pressure energy to minimize the power required to move the air [71].

Wind tunnels can be of drastically varying sizes, simulate various conditions and have a variety of geometries. Wind tunnels can be classified based on their recirculation of air, test section configuration, and operating speed ranges. Wind tunnels have one of two configurations; they can be either open-circuit of closed-circuit [70]. Open-circuit wind tunnels generally intake air from and exhaust air into the atmosphere; the air is not recirculated. In closed-circuit wind tunnels, the air path makes a closed loop in which air leaving the test section passes again through the fan and enters the test section again; air within a closed-circuit wind tunnel is not exchanged with the atmosphere [70]. The test section configuration is defined by how many solid boundaries enclose the test section; generally they can be described as closed, open, or partially enclosed (such as by one or more slotted walls) [70]. Wind tunnels are also generally defined by the operating speed range: low-speed (generally less than 300 mph) or subsonic (less than the speed of sound, Mach 1), transonic (operating range crosses Mach 1), supersonic (above Mach 1), and hypersonic (higher Mach numbers and often high altitude conditions) [70,71].

When designing wind tunnels, scaling parameters which apply to models apply also to the flow maintained within the tunnel. Airflow velocity (Mach number) and Reynolds number are the two most critical parameters for wind tunnel design [70]. Another key design metric for wind tunnels is flow quality, a term used to describe uniformity within the flow over the test section. Flow quality can be maintained through the use of a number of engineered features of the wind tunnel. Vanes are used in corners to reduce flow separation following the curve [64,70,71]. Screens, often honeycombshaped or similar, are used to reduce eddies and overall vorticity (swirling) in the flow prior to the test section [70,71].

2.3.3. Scale models in mine ventilation

Mines are very complex and irregular systems, so scale models must be applied with relative caution to mines as opposed to aircraft or automobile design. Unlike the geometry of an aircraft or production automobile, the geometry of a mine airway is less regular and much less repeatable; no two shafts are bound to have the same dimensions and features and no set of mine entries, excavated via blasting or via continuous mining from natural ground, can ever be accurately considered identical. In this sense for the purpose of modeling airflow, a scale model of an entire mine ventilation network could never be considered as accurate as, for example, a scale model of the Space Shuttle. With these irregularities in mind, scale models are applied in mining in a much more general sense than they would be in aeronautical or naval engineering. Scale models have been employed by mine ventilation engineers to analyze relatively specific systems common to mine ventilation networks, such as shafts and working headings [72-83].

Scale models have been used by mine engineers to study shaft resistances, face ventilation, auxiliary ventilation, and gob ventilation. One early study applying scale models in mine ventilation focused on shaft resistances. Gregory noted that shafts are often made to perform the roles of both ingress/egress and production and simultaneously used as part of the ventilation system [72]. Gregory held that poor aerodynamic design represented significant annual cost in the form of ventilation power requirements. He used a smoke tunnel to study the aerodynamic drag on various shapes of individual buntons (horizontal shaft dividers). Gregory also created a 20-ft long 1:12 scale model of a representative section of shaft to measure the resistance resulting from various bunton configurations. Gregory also stated that given the range of Reynolds numbers over which the wind tunnel operated (from 0.3×10^6 to 1.0×10^6) and given that the maximum flow speed was 80 ft/sec, the requirement of dynamic similarity did not apply to the model since the pressure loss coefficient for which was tested is independent of Reynolds number.

Stein et al. with the Bureau of Mines used a 1:10 scale model of an auger-type continuous miner in a low coal seam to qualitatively investigate the effects of auxiliary ventilation on dust dispersion near the mining face [74]. Breslin and Strazisar with the Bureau of Mines performed a series of studies using scaled models of mining machines in coal mines [73]. These studies used 1:5 scale models of a drum-type continuous miner and a double-drum longwall shearer and a 1:6 scale model of a twin-borer-type mining machine and made use of methane as tracer gas to model the dispersion of dust around the mining machines.

Gillies also used a scale model to investigate coal face ventilation in the laboratory [75,76], using colored smoke and bits of string to visualize airflow patterns in a 1:10 scale model of a working heading with a continuous miner. Gillies repeated the need for geometric and dynamic similarity but accepted a difference in the Reynolds number between the model and the prototype mine heading, stating that there was little difference in flow patterns between the model and the prototype. Tien similarly used a 1:10 scale model to study airflow in a continuous miner heading, this time while developing a crosscut [77]. One ½-hp fan was used to provide primary ventilation while another ½-hp fan was used to simulate the scrubber unit on the continuous miner. The model was fitted with a regular grid of holes through the rib, at several heights and distances from the working face, into which Pitot-static tubes could be inserted at various depths to yield a regular three-dimensional array of sample points throughout the model.

Uchino and Inoue used both actual and reduced-scale models to study the airflow patterns resulting from forcing auxiliary ventilation in a coal mine entry [78]. The roughly 1:16 scale model used water as a working fluid and used laser light illumination to qualitatively visualize flow patterns in the heading. Konduri et al. also used both actual and reduced-scale models to study airflow resulting from jet fans for face ventilation [79-81]. Konduri et al. also used the Reynolds criterion for scaling and used water in the reduced-scale model. Their study used colored dye, rayon strings attached to the walls and still photography to make observations about the flow patterns in the model, including re-entrainment of exhaust air into the stream from the jet fan.

Jones et al. used a scale model and computational fluid dynamics (CFD) to study gas migration through a longwall gob [82,83]. Jones et al. applied the concept of similitude to the 1:70 scale model and scaled the Peclet number (a pi term describing the ratio of molecular diffusion) and permeability in the gob accordingly. Interestingly, the model used SF_6 as a tracer gas to represent methane but because SF_6 is heavier than air and methane is lighter than air, the model results were interpreted as vertically inverted with regard to the prototype.

3. DESIGN OF EXPERIMENTAL APPARATUS

3.1. DESIGN CRITERIA AND CONSTRAINTS

Once candidate tracer gases have been identified, an experimental mine simulator will be useful for performing experiments to verify the function of the gases as tracers in a ventilation network. The experimental apparatus will be useful to simulate tracer gas surveys in a mine ventilation network. Such a model would allow for the injection and sampling of tracer gases as would be performed in an actual mine ventilation survey. The model would also allow for the measurement of air velocities at the points of injection and sampling, as such data would also be measured in an actual mine ventilation survey. Recalling Eqs. (2.12-14), atmospheric conditions (temperature, relative humidity and barometric pressure) provide a means for improving the accuracy of the velocity measurements using Pitot-static tubes. Additionally, these atmospheric conditions and air velocities will be valuable data for building a numerical model for application to actual mines, which is part of the overall project goal.

Designing, preparing and performing experiments in underground mines requires a great deal of planning and, from Virginia Tech, a fair amount of travel, such that regular visits to an underground mine for simple tracer gas experiments would be exceedingly difficult, if not time-prohibitive. The ability to perform experiments in a local laboratory setting would be far more convenient for researchers investigating these new tracer gases. An experimental apparatus for laboratory-scale testing of multiple tracer gases was deemed necessary for both convenient access to a test area and controllable conditions for experiments. In addition to the convenience of a local laboratory in which experiments would be conducted, the conditions within a laboratory are more conducive to initial investigation of novel tracer gases. Controlled conditions would allow for more accurate quantification of concentrations emitted and sampled, more stable and directly controllable atmospheric conditions, and control or at least far better knowledge of potential contaminants within the atmosphere. Controlled conditions would allow experiments in the laboratory to be conducted with better accuracy and simpler procedures limiting the introduction of error from unknown sources.

The procedures involved in tracer gas analysis are complex and the accuracy and precision of any gas analysis results are highly dependent on the technique of the analysts. Prior to field trials, which, as previously stated, require a great deal of preparation, travel and cost, researchers should have developed the proper technique to confidently expect repeatable results from their analyses. Through the performance of many tests on the experimental apparatus, located in close proximity to the GCs, researchers can practice routine sampling and analysis and develop a consistent sampling/analysis methodology prior to conducting field trials.

Several criteria for this tracer gas study preclude sole reliance on a CFD model. The first and most important reason for a physical model is for developing the technique of gas sampling and analysis. Recalling from the literature review, CFD has some shortcomings as a modeling tool. Boundary conditions should be well-understood prior to the creation of a model. CFD also has difficulties modeling turbulence, which is extremely important in the description of the dispersion of tracer gases. Furthermore, the diffusion and dispersion of tracer gases are controlled by the molecular weights and other properties of the gases. These properties may be ill-defined for gases which have not been used extensively as tracers and may be not be accurately reflected in the assumptions included in the CFD program.

3.1.1. EXPERIMENTAL GOALS

Given the expectations of the laboratory experimental apparatus, a simple list of necessary criteria can be laid out for the apparatus. The experimental apparatus for tracer gas investigation should

1) simulate a mine in a tabular deposit,
2) allow for the injection and sampling of appropriate amounts of tracer gases,
3) simulate changes in ventilation (as after a mine disaster) by incorporating simple variable ventilation controls, and

4) allow for the measurement and monitoring of air velocities (quantities) and atmospheric conditions (temperature, relative humidity and barometric pressure) within the apparatus.

This list of criteria should be considered the goals of the apparatus; they represent the criteria which must be met in order for the apparatus to be considered a sufficient model mine for the purposes of tracer gas testing.

3.1.2. Design constraints

A number of constraints were placed on the design of this experimental apparatus. The apparatus should simulate a mine in a tabular deposit topologically and by maintaining fully-developed turbulent flow throughout the apparatus. The apparatus should have ports for the injection and sampling of tracer gases in the system. The ventilation system should feature an appropriately-sized fan and functioning ventilation controls. The ventilation system must also be airtight and open-circuit so that tracer gases can be exhausted from the laboratory atmosphere rather than building up within the laboratory gaseous background and obscuring concentration results. The design should also be able to simulate various mine topologies in order to perform experiments on a wide variety of mine layouts. In order to simulate many mine layouts, the experimental apparatus would need to be altered. To limit the amount of effort associated with altering the experimental apparatus, the apparatus should be modular in construction so that it can be changed quickly and with little reconstruction of permanent fixtures.

3.2. Evaluation of design alternatives

3.2.1. Alternative designs

Given the four goals and additional constraints defined for the experimental apparatus, a number of alternative designs were evaluated based on their ability to meet those requirements. With focus on the geometry of a mine in a tabular deposit, various design geometries were considered. The geometries under consideration ranged from completely dimensionally representative of the prototype mine (most geometrically similar to the prototype mine) to more loosely representative (less geometrically similar).

The first design considered was an entirely flat grid which would be most representative of a mine in a tabular deposit. For this design, a flat plate of material such as Plexiglas would be used for the top and bottom of the deposit (the upper and lower bounds of the mine entries) and rectangular inserts would make up the walls. Entire sections of a mine could be modeled this way while maintaining geometric similarity to the prototype mine. The plates bounding the top and bottom of the model could be notched or grooved in a grid such that the walls could be easily inserted and removed. Holes could be drilled through the top bounding plate through which velocity measurements could be made and tracer gases could be injected or sampled.

The flat grid design has a number of disadvantages, however. The flat design would necessarily require a large footprint, especially if constructed horizontally. The entire model could be used vertically near a wall or horizontally in an area near the ceiling. Even if the mining height in the model was 0.5 in., the expanse of a scale model representing an operating longwall mine would be at least several to tens of feet in each direction. These dimensions would preclude vertical orientation (as the ceiling height is less than ten feet) and horizontal orientation near the ceiling (where the largest footprint is available) would leave the model very inaccessible. Additionally, sealing the apparatus in a way which renders it airtight could be difficult, especially in separating the airways from one another. Though some leakage between parallel airways would be representative of an actual mine ventilation network, controlling internal leakages in the apparatus could prove very difficult. Such a model, though modular, would not be very simple.

A simpler version of this full-scale model could be constructed in which the airways are based on a simpler network topology. A simplified model between two flat plates would have the same advantages as the larger scale model except for its good geometric similarity. A simpler model would use less material and could remain modular, with its parts able to be moved fairly simply. Such a model would still be fairly difficult to seal, however, with many loose parts needing to line up precisely or sealed to be made airtight. Having to seal many dividers serving as walls would make the disassembly and reassembly of the apparatus take more difficult and require more time, but may be necessary to keep the model airtight.

Furthermore, in a flat model, regardless of scale, ventilation controls would all be uniquely constructed and more difficult to seal and maintain. Placing variable ventilation controls such as a regulators or stoppings which can simulate damage will likely require making openings in one of the flat plates bounding the apparatus, rendering it harder still to seal. Ventilation controls for a flat model would need to be uniquely constructed and as such would be difficult to maintain.

Relaxing the constraint of the apparatus being entirely planar allows for more options for the apparatus. If the vertical displacements are kept to a minimum (as they would have to be in a laboratory with vertical extent of less than ten feet), some extension into the vertical plane would allow sections of the airways to overlap one another, allowing for more airway length with a smaller footprint. Though this design could carry on a similar planar form with multiple levels, the planar concept could be discarded altogether while maintaining topological fidelity to a prototype mine. In this sense the geometric constraints could be relaxed until it could be represented by a network of discrete airways. Recall that mine ventilation networks are often, for the purpose of modeling and analysis, represented by a network of discrete airways. Such a network of discrete airways is frequently constructed in HVAC as a duct network.

A duct network could represent a simplified mine geometry by being topologically identical while allowing for some geometric variation, particularly by relaxing the constraint that the model be entirely coplanar. Duct networks are easily rendered airtight and, depending upon the materials used, ventilation controls such as dampers or valves are ubiquitous for ducts of most sizes and shapes. This would mean that individual ventilation controls need not be uniquely fabricated and then made airtight. Ducts are available in many materials and cross-sectional shapes and sizes. Ducts are easily integrated with fans and can be easily assembled and disassembled.

The disadvantage of using a standard home or commercial duct system is that the ducts have a relatively large cross-section (10^1~10^2 in.^{2}). Creating a network from typical home ventilation ducting with multiple branches that is long enough to represent a mine ventilation system could require a significantly large volume, even if tightly wound upon itself. Also most available duct material does not have the same cross-sectional shape as a coal mine entry: some ducts are rectangular, some are square and some are circular. Pipe could also be used instead of circular duct; pipe would have approximately the same advantages and disadvantages as ventilation duct but is available in a generally smaller cross-section.

A summary of the design alternatives is provided in Table 3-1. The **Planar, to scale** option represents the most geometrically similar model to a working mine in a tabular deposit but in turn would be the most difficult to work with. The **Simplified pipe network** represents the design with the geometric similarities most relaxed but which is the simplest and easiest to work with and make airtight. Between those two options are design options representing two inner points on the spectrum, the **Planar, simplified** and **Simplified duct network**. Keeping in mind the overall goal of the apparatus serving in tracer gas experiments, the topological fidelity of the model to the prototype should take precedence over the geometric similarity. It is most important that the tracer profiles created in the apparatus be representative of those resulting from actual mine tracer gas surveys. Furthermore, the ability to be made airtight with relative ease is very important in the laboratory. Having tracer gases leak slowly from the apparatus will negatively affect all the tracer gas experiments conducted in the lab. Finally, the ability to potentially make use of off-the-shelf parts makes the **Simplified duct network** or **Simplified pipe network** options the most preferable. In choosing duct or pipe, the many options for materials should be evaluated.

TABLE 3-1: COMPARISON OF DESIGN ALTERNATIVES

Model Type	Advantages	Disadvantages
Planar, to scale	• Geometrically similar • Parallel airway leakages easily included • Modular	• Full mine to scale too large to fit in lab • Difficult to make airtight • Ventilation controls difficult to make and seal
Planar, simplified	• Airway shape similar • Parallel airway leakages easily included • Modular	• Difficult to make airtight • Ventilation controls difficult to make and seal • Difficult to access
Simplified duct network	• Modular parts/ventilation controls available off-the-shelf • Easy to make airtight • Simple to work with	• Airway geometry not identical to mine geometry • Most duct too large
Simplified pipe network	• Modular parts/ventilation controls available off-the-shelf • Easy to make airtight • Simple to work with	• Airway geometry not identical to mine geometry • Metal pipe could be most expensive

3.2.2. MATERIALS SELECTION

As mentioned along with the design alternatives, various materials were evaluated for their appropriateness for constructing the apparatus. Since a network of discrete airways was decided to be preferable to a modular flat grid, sections of duct or pipe would be appropriate materials. Duct and pipe are available in many different sizes (diameters) and cross-sectional shapes. The materials evaluated were galvanized steel duct, aluminum duct, Plexiglas, copper tubing, steel tubing, and PVC pipe. Given that the apparatus was designed to be disassembled and reassembled, the effort in achieving an airtight seal and the availability of connections or flow controls off-the-shelf were important factors. Cost of materials and components was also considered.

Galvanized duct is available with either a rectangular or round cross-section, which could approximate the rectangular cross-section of a mine airway. The duct could also be reshaped to better represent mine airway dimensions, but would then be more difficult to maintain as airtight. The galvanized duct is simple to connect with other sections and tees and wyes are available off-the-shelf, so long as the duct is not reshaped.

Dampers manufactured for galvanized duct are available off-the-shelf but would need to be uniquely constructed if the duct was reshaped. Flow controls for home HVAC also tend to allow some leakage, so stoppings inside the apparatus may not meet the same resistance requirements as controls in a mine. Galvanized duct for home HVAC also tends, as previously mentioned, to have a relatively large cross-sectional area. This suggests that building a model with a length-to-diameter ratio approximately matching that of a mine would require a great deal of large-diameter duct, which would require a large volume of space to build.

Aluminum duct would have approximately the same characteristics as galvanized steel duct. Though aluminum duct is available in most of the same dimensions as galvanized duct, it may be available in a slightly different array of possible shapes and sizes. Aluminum duct would be somewhat lighter and easier to work with, but likely a bit more expensive.

Plexiglas or other acrylic materials are available in round and square tubes as well as sheets, from which tubes of any cross-section could be fabricated. Plexiglas and acrylic tubing could be easily cut to length and easily attached to other pieces and made airtight. Most connections and ventilation controls for a Plexiglas system would need to be uniquely fabricated, which detracts from the modularity of a design using Plexiglas components. Plexiglas is lightweight and easy to work with and offers the benefit of being transparent, which would make it easier to understand and explain the way the model works.

PVC pipe is available in round and, to a limited extent, square cross-sections. PVC pipe is the most inexpensive material investigated and is easily available off-the-shelf. An extensive range of fittings for round pipe from reducers to wyes and tees and several various valves are also readily available off-the-shelf. PVC is also lightweight and very easy to assemble and to render airtight. PVC is very simple to cut to length though it is not very flexible.

Copper pipe is available in round cross-section with relatively smaller diameter. Copper pipe has fittings available off-the-shelf, including a wide variety of valves. Copper pipe is more difficult to work with than the other materials and requires either soldering or special fittings to create airtight connections. With the difficulty in making connections, copper pipe is not conducive to a modular design. Copper is also the most expensive of the materials and the simple no-solder connectors are very expensive.

Steel tubing is available in round, square or rectangular cross-section in various diameters. Steel tubing is heavy and difficult to work with and also fairly expensive. Steel tubing is similar to the HVAC duct but is thicker and not made to be connected without welding or bolting together. Although some connectors may be available for steel tubing, their availability and cost depend highly on the dimensions used. Ventilation controls from ducts could be useful with steel tubing, but are less likely to fit exactly and more difficult to make airtight.

A comparison of the attributes of various materials is included as Table 3-2. Copper pipe and steel tubing were eliminated based on cost and difficulty to work with. The ducts were eliminated based on the volume they were likely to occupy. Plexiglas would have proved more difficult fabricate, especially to fit with airtight ventilation controls. PVC pipe (2-in. diameter) was selected as the material from which the model would be constructed. There are many benefits to PVC pipe over other materials: PVC is considerably cheaper than aluminum or steel tubing, simple to handle due to its light weight, simple to cut to desired length and simple to connect via couplings, elbows and tees. A wide variety of valves, reducers and other fittings are available in local hardware and plumbing stores and are inexpensive enough to maintain a supply of fittings in the lab. PVC can withstand the relatively small pressures applied by the simple laboratory ventilation system and can easily be made airtight by applying sealant, caulk or duct tape. Sealed in such a way, PVC pipe is also simple to separate, clean, and reassemble for rearranging the geometry of the model. For these reasons, PVC makes an excellent material for the tracer gas test apparatus.

TABLE 3-2: COMPARISON OF MATERIAL ALTERNATIVES

Material	Cross-Section	Cost	Difficulty in Assembly	Ventilation Controls
Galvanized steel duct	rectangular, round	medium	low	some available, hard to make airtight
Aluminum duct	rectangular, round	medium	low	some available, hard to make airtight
Plexiglas/ acrylic	square, round, (sheet)	medium	medium	must be uniquely fabricated, hard to make airtight
PVC pipe	round, (square)	low	medium	wide variety available off-the-shelf
Copper pipe	round	high	high	wide variety available off-the-shelf
Steel tubing	round, square, rectangular	high	high	could use duct controls, difficult to make fit/airtight

Additional concerns arise for the materials selection to include appropriateness for use in the apparatus with tracer gases. Two material properties which affect how tracer gases behave in the apparatus are the surface roughness (ability to create and sustain highly turbulent flow) and the adsorption characteristics of the gas and material. The first property, surface roughness, represents only a minor hurdle in the design. The flow regime in the apparatus is affected by the roughness of the walls but also controlled by the Reynolds number. As was demonstrated in the discussion of similitude, turbulent flow is created and maintained throughout the apparatus.

The second materials property, adsorption characteristics, is an interfacial property that is controlled by the physical and chemical properties of both the gas and the solid surface. Recall that initial results from early tracer gas experiments did not show any significant adsorption of SF_6 onto mine surfaces [1]. Recall also, that adsorption is always observed to occur between any gas-surface pair [7]. No significant measurement of adsorption of SF_6 has been demonstrated in laboratory results, though there is some anecdotal evidence that SF_6 adsorbs onto PVC, glass and plastics including chemical containers and syringes [10].

3.3. Location and Orientation of Apparatus

The space available for the construction of the apparatus, in the ventilation laboratory at the Mining and Minerals Engineering Laboratory on Plantation Road, provided some spatial constraints. While the size of the room is certainly large (19 ft × 48 ft), there is a roughly 4-ft-high, 4-ft-deep shelf along three sides of the room, leaving significantly less floor space in the center of the room for equipment and experiments. Figure 3.1 shows the floorplan of the ventilation lab from architectural drawings. In addition to the space at one end set aside as a classroom, the lab also contains two workbenches atop which the gas chromatographs (GC) and a PC rest, an area adjacent to the GCs for gas cylinder storage, two workbenches for experiments, a desk for manometers and tools, and four permanent wind tunnel experiments set up in the space, each with a fan (either centrifugal or axial-vane) with an electric motor and a length of duct.

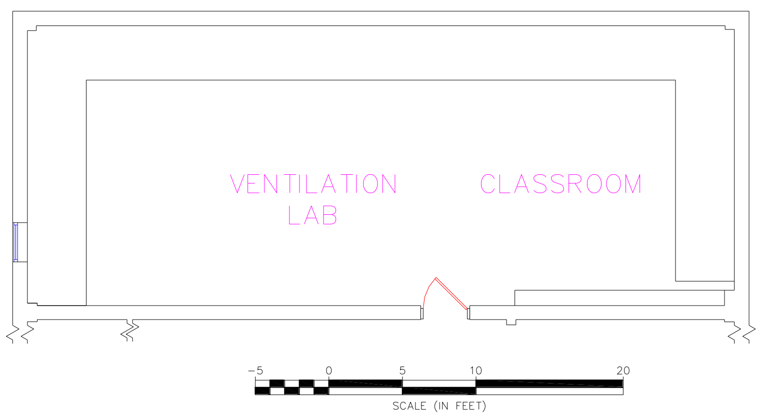

FIGURE 3.1. FLOORPLAN OF VENTILATION LABORATORY

With limited remaining floor space in the laboratory, a vertical orientation was chosen for the apparatus layout in order to minimize the footprint of the apparatus. The resulting configuration appears as dual, vertical stacks of tubes, connected continuously and bolted to the frame of the large wind tunnel. The layout of the new tracer gas test apparatus with respect to the other existing wind tunnels is shown in Figure 3.2. The proximity of all the equipment in the laboratory equipment is apparent, as one wind tunnel was already installed suspended from the ceiling directly above another due to floor space constraints.

FIGURE 3.2. CONFIGURATION OF TRACER GAS TEST APPARATUS IN LABORATORY WITH RELATION TO OTHER WIND TUNNEL EXPERIMENTS

3.4. EVALUATING MODEL VALIDITY VIA TOPOLOGY AND SIMILITUDE

In order to evaluate the validity of the experimental apparatus as a model, criteria must be selected which, if fulfilled, constitute reasonable representation of a mine ventilation network. Here the author uses 'representation' as opposed to 'similarity,' by which the author refers here only to the 'similarity conditions' required for similitude. The two criteria for representation of a mine ventilation network are fidelity to topology and in similarity of geometric and dynamic conditions comprising similitude. In assessing the relative importance of the conditions of accurate representation, recall that mine ventilation networks are most frequently modeled as networks of resistances rather than individual airways; rarely is very accurate modeling of individual airways of significant importance to the numerical solution of the entire network. Given the nature of mine ventilation surveys, in which air quantities are accounted for via a network balance, fidelity to the topology of a mine should be the primary priority of the criteria for accurate representation of a mine. The similitude requirements represent a secondary priority for assessing the validity of the model. The significance of the geometric and dynamic similarity requirements is primarily in demonstrating that similar flow conditions are present in the model as occur in an actual mine; those flow conditions are fully-developed highly turbulent conduit flow. For this reason and for the sake of thoroughness are similitude and entrance length considered conditions for valid representation of the mine by the model.

3.4.1. Topological Fidelity

A typical longwall coal mine ventilation system was chosen as the basis for the first simple mine model. A simplified ventilation network with one active panel and one gob panel was selected for the model and the model was constructed from 2-in.-diameter PVC pipe. Figure 3.3 shows a layout of the mine used as a basis for the experimental model. Figure 3.4 is a schematic of the model as constructed in the laboratory. The figures are color-coded to highlight the topological similarity between the simplified mine geometry and the physical model. For the purpose of simplicity, only flow around the gob panel was modeled, rather than flow through the gob panel. Modeling flow through the gob panel would add a number of complications, including considering a porous medium which is representative of a longwall gob on the model scale and accounting for the significant pressure drop across such a medium and the potential adsorption of the tracer gases onto the porous medium.

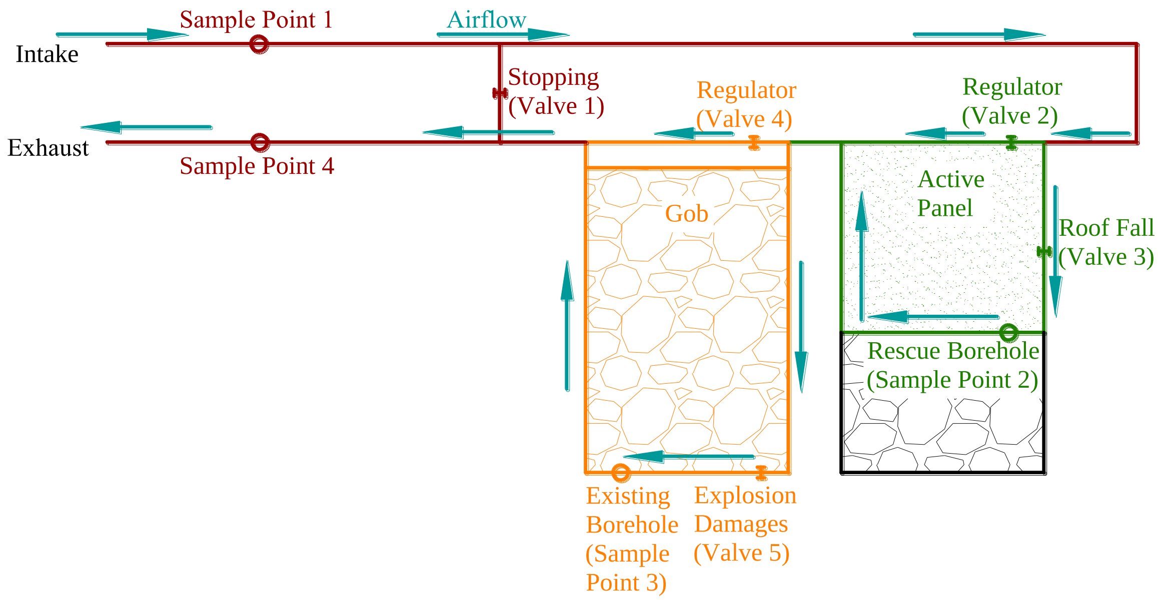

FIGURE 3.3. SIMPLIFIED MINE GEOMETRY USED AS BASIS FOR MINE MODEL

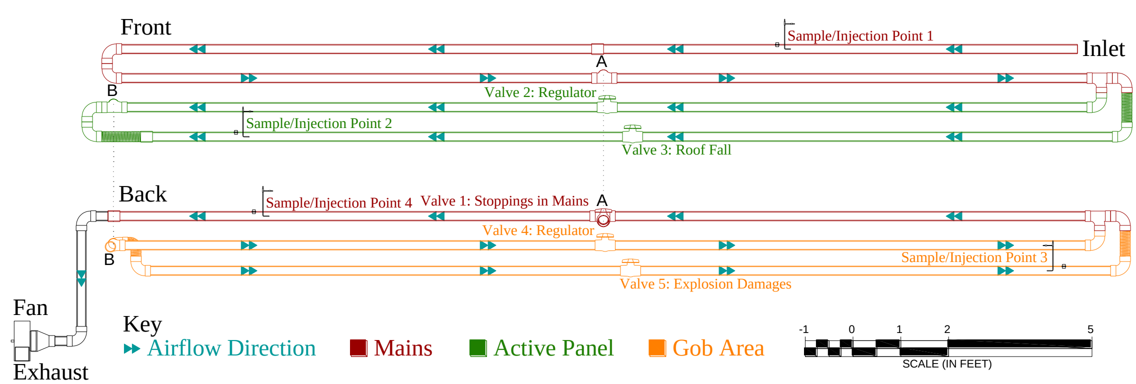

FIGURE 3.4. MINE MODEL SCHEMATIC WITH COLORS CORRESPONDING TO SIMPLIFIED MINE GEOMETRY

It is important to recognize how the model and simplified mine geometry are topologically identical. Both feature parallel intake and exhaust entries (mains), which are connected via a normally close valve representing stoppings in the main entries. An actual coal mine which is mined via room and pillar mining has several parallel entries making up the mains, of which some are used for the transportation of intake (fresh) air and some are used for the transportation of return (exhaust) air. Those entries which conduct air of the same type in the same direction (either all of the intakes or all of the returns) are connected such that for the purpose of simplicity, they can be modeled collectively as one branch in the network. There is a very small but usually realistically non-negligible leakage from the higher-pressure intakes to the lower-pressure returns, which underground takes place across hundreds of parallel stoppings separating the intake and return airways. Topologically, and again for simplicity, these are collectively represented by one branch of variable resistance (a valve). In the simplest case, this valve could be completely closed, though it could be slightly open to simulate the small leakage quantity across the stoppings. In the case simulating the destruction of some stoppings due to high air overpressure resulting from an explosion, the valve could be opened to simulate the loss of some stoppings. The resulting network topology, with a much-lower resistance connection effectively short-circuiting airflow between the main intakes and returns, is shown in Figure 3.5.

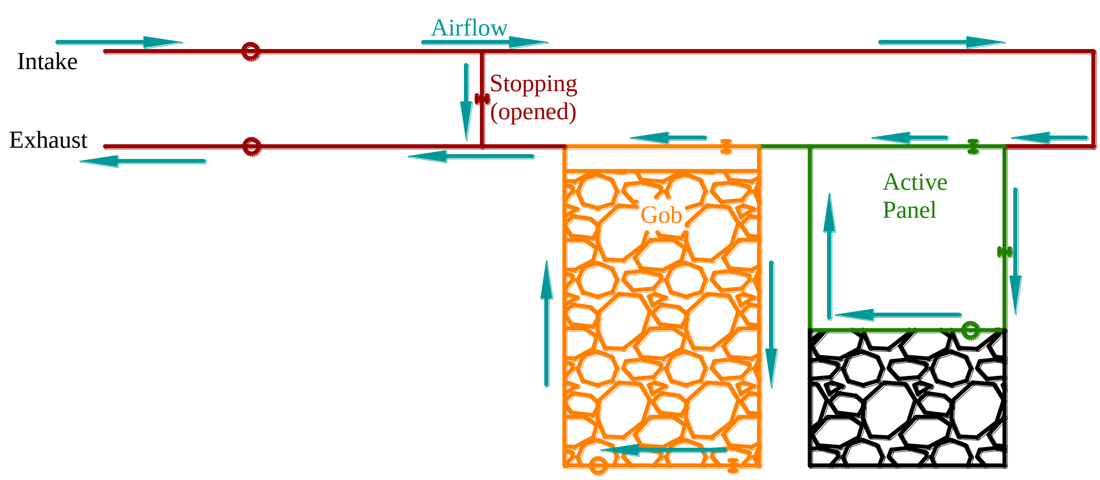

FIGURE 3.5. MINE MODEL GEOMETRY AND AIRFLOW RESULTING FROM LOSS OF STOPPINGS ALONG MAINS

Both the working panel and the gob panel are represented by independent loops which run parallel to the main intake/exhaust series. For each panel, the branch representing the panel is fitted with a regulator, as is the branch on the mains parallel to that panel. These resistances should be adjusted to achieve a representative quantity split such as would be present in an actual mine ventilation network. In a mine, the desired quantity split would be controlled similarly by adjusting the resistance of the working or gob panel split via regulators. The valves in these panels can also be changed to reflect the conditions resulting from a disaster, such as an increase in resistance in an airway resulting from a roof fall. To represent such an increase in resistance, the valve on a particular airway need only be closed more significantly.

Locations for injection and/or sampling of tracer gases were selected in the intake airway, in the exhaust airway, in the active mining panel and in the (entries around the) gob panel. The injection of tracer gas could take place within the intake entry or at the top of the intake shaft at an actual mine. Similarly, the sampling of air for tracer gases could take place within a return entry or at the exhaust shaft at an actual mine. Air sampling at the intake might take place for purposes of establishing a background concentration, but otherwise sampling at the intake or injecting into the return would serve no purpose for a tracer gas ventilation survey. Within the active mining and gob panels, gases would most likely be injected (but could, for some purposes, be sampled). The injection or sampling in the active panel would take place along or near the face under normal conditions or possibly through a rescue borehole following a disaster after which the mine personnel have been evacuated. Sampling or injection around the gob panel could take place within the entries exhausting the gob or via an existing gob gas monitoring borehole, if such boreholes exist at the particular mine.

3.4.2. SIMILITUDE IN THE APPARATUS

Recognizing the importance of similitude in engineering models, similitude between the model and a typical longwall mine was studied. Recalling the pi terms for similarity, the geometric scale should be considered along with the Reynolds number. Examining a typical coal mine entry, assuming airway dimensions of 5 ft high by 20 ft wide, the area is given as

$$A = H \times W = (5\text{ ft}) \times (20\text{ ft})$$
$$A = 100\text{ ft}^2 \qquad \text{Eq. (3.1)}$$

and the hydraulic diameter, from Eq. (2.10), is given as

$$D_H = \frac{4A}{O} = \frac{4(100\text{ ft}^2)}{(50\text{ ft})}$$
$$D_H = 8\text{ ft}. \qquad \text{Eq. (3.2)}$$

An estimate of the length-to-diameter (L/D) ratio of an underground mine, with a total airway length of several miles, can be found as

$$\frac{L}{D} \approx \frac{L}{D_H} \approx \frac{(10^4 \text{ ft}^2)}{(8 \text{ ft})} \approx \frac{(10^4 \text{ ft})}{(10^1 \text{ ft})}$$
$$L/D \approx 10^3. \qquad \text{Eq. (3.3)}$$

The result of Eq. (3.3) shows that in order to successfully model an underground mine, the diameter (L/D) ratio of the models' airways should be very high, perhaps on the order of 10^3. Literature estimates Reynolds numbers in mine airways as generally exceeding 10^4 and stresses that fully turbulent airflow nearly always prevails in mine airways [60,61].

PVC pipe of 2-in. diameter was used in an exploratory model to investigate the viability of a centrifugal fan in the lab. Using 2-in. diameter pipe, in order to maintain an acceptable degree of similitude, the total length of pipe needed for the model can be calculated by

$$\frac{L_M}{D_M} = \Pi_{1M} = \Pi_{1P} = \frac{L_P}{D_P}$$
$$L_M = D_M \frac{L_P}{D_P} = \left(\frac{2}{12}\text{ft}\right)(10^3) \approx (10^{-1}\text{ft})(10^3) \qquad \text{Eq. (3.4)}$$
$$L_M \approx 10^2 \text{ ft}.$$

This result shows that for a model using 2-in. diameter pipe, ~10^2 ft (hundreds of feet) of pipe can represent 10^5 ft (miles) of mine airway. Given that the model currently contains approximately 160 ft of pipe, the model is sufficiently geometrically similar to a mine airway a few miles in length.

Examining the air velocities in the model, the Reynolds number of the flow can be calculated. Given that average velocities in the model were measured to be approximately 8 m/s (26 ft/sec), the Reynolds number can be found by applying Eq. (2.9)

$$\text{Re}_M = \frac{\text{VD}}{\nu} = \frac{(\sim 26 \text{ ft/sec})(2/12 \text{ ft})}{(3.74 \times 10^{-4} \text{ ft}^2/\text{sec})} \approx 1.16 \times 10^4. \qquad \text{Eq. (3.5)}$$

Using the dynamic similarity criterion

$$\mathrm{Re}_M = \Pi_{2M} = \Pi_{2P} = \mathrm{Re}_P$$
$$\mathrm{Re}_M \approx 1.16 \times 10^4 \approx \mathrm{Re}_P \geq 10^4 \qquad \text{Eq. (3.6)}$$

it can be concluded that the model Reynolds number of $\mathrm{Re}_M \approx 1.16 \times 10^4$ is representative of the flow regime in a mine airway. Furthermore, given that

$$\mathrm{Re}_M \approx 1.16 \times 10^4 > \mathrm{Re}_{critical} = 4000, \qquad \text{Eq. (3.7)}$$

the flow in the model airway can be considered within the fully-developed turbulent regime. Maintaining turbulent flow throughout the model is important to insure that tracer gases disperse fully in the airstream so that measured gas concentrations are representative of the whole airstream.

It should be noted that the geometric similarity of airway cross-sectional dimensions (W/H) is not conserved in the model; the model airway is circular while the mine entry is rectangular in cross-section. In this sense, the model cannot be considered an entirely true model by definition. However, given that the ratio (W/H) is somewhat variable among mines with different mining heights and entry widths, this constraint should be considered far less important than the vital constraints of the (L/D) ratio and the Reynolds number. Based on similarity between these two values, the experimental model should be considered a nearly true model, distorted only in the cross-sectional geometric ratio.

It is not the goal of this model to perfectly simulate mine airflow in any given section of the model or mine. It should be considered sufficient that the model topologically represents a realistic mine and that turbulent flow is maintained throughout the model because the primary interests are in the tracer profiles and ensuring mixing that is similar to mine conditions. A detailed CFD model of the apparatus was made to help predict tracer gas profiles under various ventilation control conditions. Initial experiments using tracer gases, along with the CFD model showing turbulent flow in the apparatus, demonstrated tracer concentrations which reflect complete diffusion of the tracer in the airway [84].

3.4.3. ENTRANCE LENGTH

Given that turbulent flow is necessary for the complete dispersion of tracer gases, it is worth estimating the length of duct required before fully-developed duct flow dominates. Recalling Eq. (2.11), the entrance length required for conduit flow to fully develop can be estimated by

$$L_e = 4.4(Re)^{1/6}D \approx 4.4(1.16 \times 10^4)^{1/6}D \approx 126D = 21\text{ ft.} \qquad \text{Eq. (3.8)}$$

Although Eq. (3.8) estimates an entrance length of 126 diameters, recall that Lien, et al. recommend a conservative estimate of 130-150 diameters for the development of fully-turbulent flow [65]. Conservatively, turbulent flow can be assumed to be fully-developed at a distance from the inlet of

$$L_{e(max)} = 150D = 150(2/12\text{ ft}) = 25\text{ ft.} \qquad \text{Eq. (3.9)}$$

Given that the inlet section is just over 20 ft long and followed by a section of turns, it can therefore be assumed that so long as the velocity is such that turbulent flow is maintained ($\mathrm{Re}_M > \mathrm{Re}_{critical} = 4000$), fully-turbulent flow dominates throughout the rest of the apparatus.

4. Construction and Instrumentation

4.1. Construction

Recalling the design constraints and the four criteria comprising the experimental goals, the apparatus was constructed such that it sufficiently satisfied the experimental goals while maintaining the ability to be rearranged with relative ease. The ideal constraints of maintaining simplicity and modularity were respected throughout the construction. For the sake of simplicity, the fewest materials should be used to create the simplest reasonable configuration. By keeping the apparatus modular, the fewest materials should be wasted (via cutting, etc.) in order to disassemble the apparatus and reassemble it in another configuration representing another mine geometry. The connections should also be as simple as reasonably possible and require the least amount of preparation to be constructed and later disassembled and reassembled.

4.1.1. Structure of pipe network

To meet the requirements for modular design and simple rearrangement, the sections of pipe representing various airways should be mounted to a frame which allows for both the easy removal and the secure mounting of the pipes sections. A frame of slotted angle iron was selected, unto which the pipe sections could be secured using U-bolts. Figure 4.1 shows the inlet end of the apparatus, in which the support frame and mounting U-bolts are clearly visible. The support frame has more space for expansion to build more complicated models in the future. In order to maintain modularity, an attempt was made to maintain the 10-ft sections of pipe intact to minimize cutting and waste and maximize their reusability regardless of what fittings were placed in line with the pipe sections. In order to then compensate in the differences in lengths of pipe sections which needed to be combined, sections of flexible shop vacuum hose, also visible in Figure 4.1, were used to connect the pipe sections which did not line up precisely. Vacuum hose was selected with an O.D. matching the O.D. of the PVC pipe so that the hose could be used with the existing pipe fittings. Care was taken to fully seal the vacuum hose connections using silicone since the ribbed surface seemed less likely to seal inside the pipe fittings.

All connections were sealed using PVC cement and/or silicone caulk to maintain airtightness of fittings.

FIGURE 4.1. SUPPORT FRAME FOR TEST APPARATUS

4.1.2. INJECTION/SAMPLING PORTS AND PITOT-STATIC TUBE MOUNTS

Several locations were identified as appropriate for the injection or sampling of tracer gas. These sample ports, which simulate boreholes in an actual mine, make use of ½-in.-diameter threaded nylon fittings which intersect the main airway perpendicularly. These sampling/injection ports are sealed with septa, rubber seals which are used to cover laboratory containers and serve to maintain an airtight seal after being pierced with a syringe needle or solid-phase microextraction (SPME) fiber. Adjacent to the sampling/injection port is a Pitot-static tube, which serves to measure the air velocity at the sampling point. A sampling/injection port with adjacent Pitot-static tube is shown in Figure 4.2.

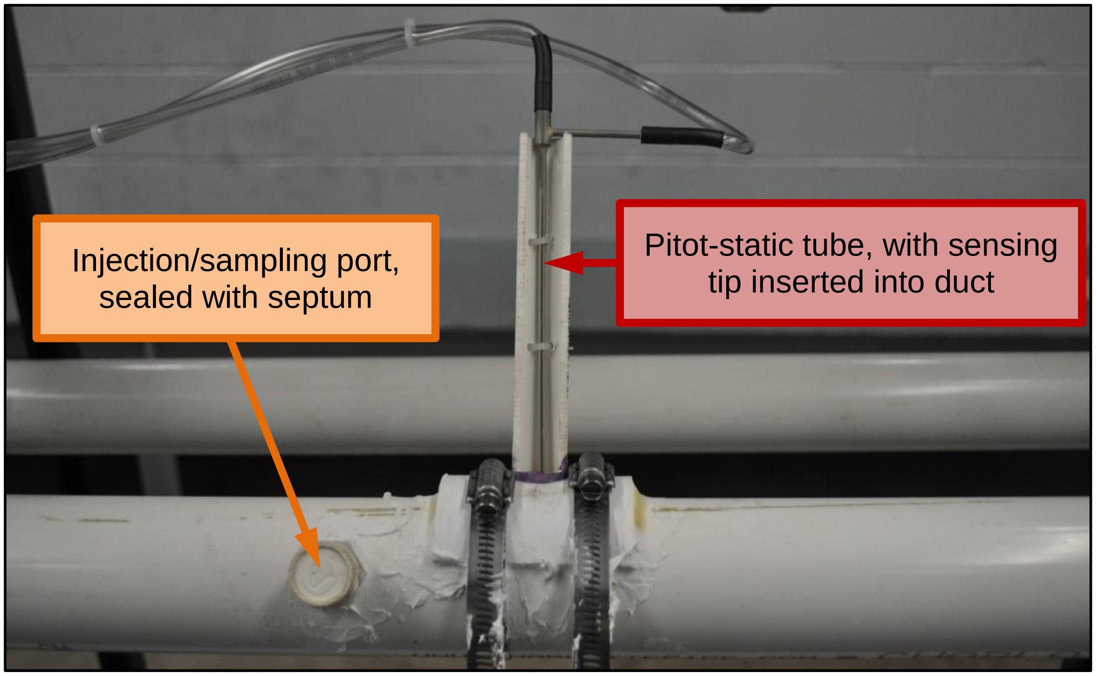

FIGURE 4.2. SECTION OF TEST APPARATUS SHOWING INJECTION/SAMPLING PORT AND PITOT-STATIC TUBE (SIDE VIEW)

When mounting a Pitot-static tube, the orientation and position of the sensing tip in the duct are important factors which have a result on the accuracy of the velocity measurement. Since the insertion depth of the Pitot-static tube (6 in.) is far longer than the radius of the pipe (1 in.), most of the Pitot-static tube (~5 in.) protrudes outside the pipe and must therefore be supported. The Pitot-static tube is arranged such that the sensing tip is in the center of the airway, so the tube must be secured with respect to the insertion depth into the pipe. The velocity measurement is also sensitive to the yaw of the Pitot-static tube (the angle the sensing tip makes with airflow direction), so the tube must be secured against rotation. The brace for the Pitot-static tube is a section of ½-in.-diameter PVC pipe split longitudinally and cemented to a section cut from 2-in.-diamter PVC pipe. Between the Pitot-static tube brace and the pipe making up the model airway, a section of rubber gasket is used to form an airtight seal around the hole through which the Pitot-static tube protrudes. Hose clamps are used to hold the Pitot-static tube brace to the model pipe and serve to compress the gasket, which forms a tighter seal around the Pitot-static tube. The long stem of the Pitot-static tube is attached to the brace with cable ties. A disassembled cross-sectional diagram of the Pitot-static tube, gasket and brace is provided as Figure 4.3.

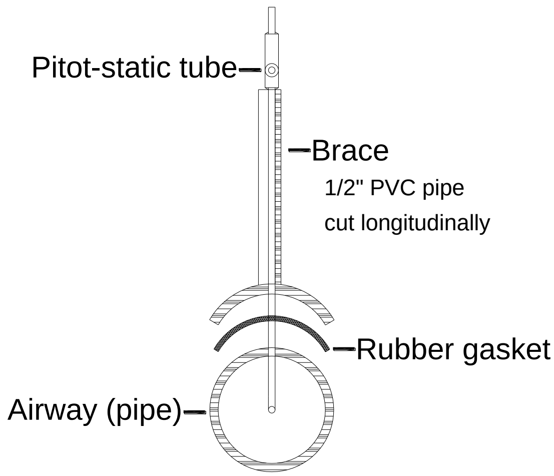

FIGURE 4.3. DIAGRAM OF PITOT-STATIC TUBE BRACE
(DISASSEMBLED, FRONT VIEW)

4.1.3. OPEN-CIRCUIT VENTILATION OF THE APPARATUS

As stated previously, one of the goals of the experimental apparatus is that it be open-circuit and exhaust to an area outside the ventilation lab. This is necessary so that tracer gases do not build up in the gaseous background within the lab and complicate or add error to tracer gas sampling over time. The ventilation system selected for the apparatus is an exhausting system for two reasons. First, the exhausting system is most common in coal mines, of which the test apparatus should be representative. Second, by being set up as an exhausting system, the ventilation system of the apparatus is maintained as a negative-pressure system. By maintaining a negative pressure system, any leaks in the system would result in lab air leaking into the system, rather than air containing tracer gases leaking from the apparatus into the lab air.

As part of the initial construction of the apparatus, a small centrifugal fan was used was used to provide the ventilation. This fan was fairly small and light and, as such, could be placed directly in the fume hood. Figure 4.4 shows the original centrifugal fan operating in the fume hood. Although raised for clarity in the photograph, the sash would be lowered while using tracer gases in the experimental apparatus to reduce the possibility of tracer gas diffusing into the laboratory atmosphere.

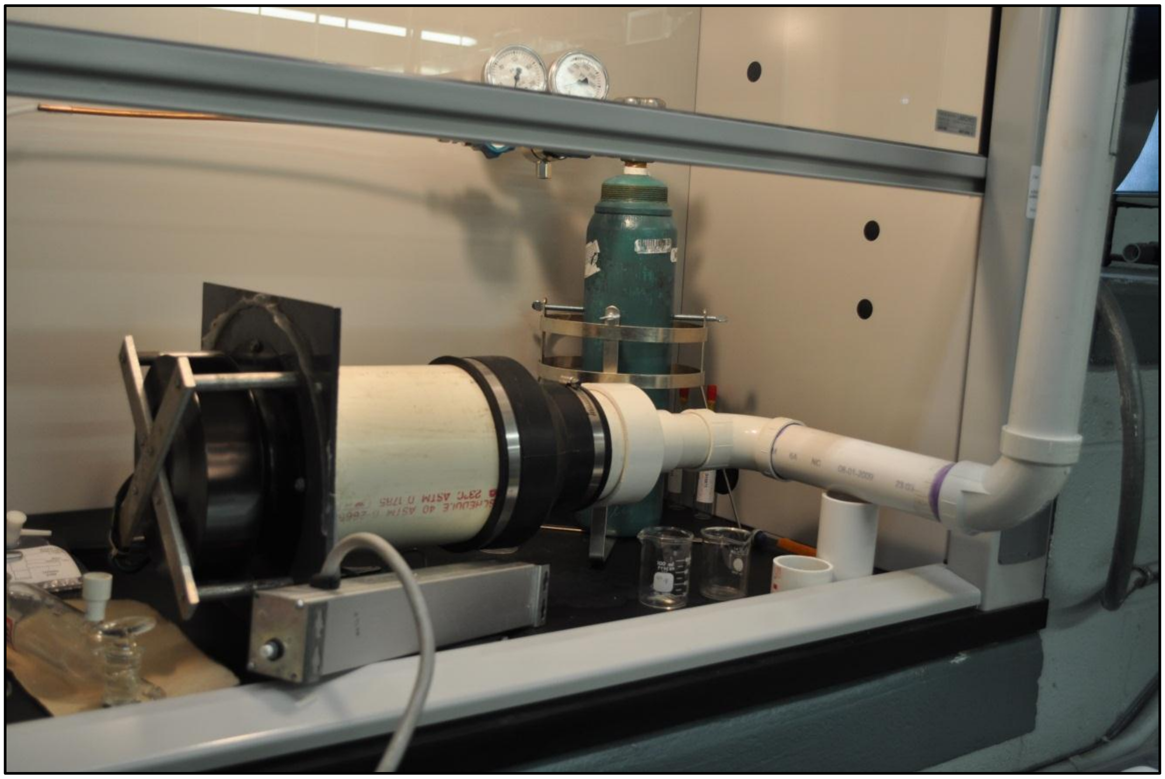

FIGURE 4.4. SMALL CENTRIFUGAL FAN PLACED DIRECTLY IN FUME HOOD

4.2. INSTRUMENTATION

Since reliable measurements for air velocity and air density were desired, instrumentation would be used for the apparatus. The instrumentation would be electronic and automated such that air velocities throughout the mine model and atmospheric conditions could be monitored and recorded while researchers were performing other tasks, such as coordinating injection and sampling of the tracer gases. Given that a small cross-sectional area would be used for the airways to simulate the very large L/D ratio in a mine, the instrumentation measuring velocities would need to be fairly small in order to measure the velocity without seriously disturbing airflow. For this purpose, Pitot-static tubes were selected for air velocity measurement, since Pitot-static tubes with a small cross-sectional area are easily acquired and are simple to instrument.

The instrumentation selected for the apparatus included Pitot-static tubes with differential pressure transducers, a barometric pressure transducer, and a combination relative humidity (RH) and temperature transducer (RH/T). A programmable logic controller (PLC) was selected to monitor the instruments and aid in recording the velocity data. A summary of the selected instruments is given in Table 4-1. Selected technical specifications for the instrumentation are included as Appendix A.

TABLE 4-1: OVERVIEW OF INSTRUMENTATION

Instrument Type	Manufacturer/Model	Range/Attributes
Pitot-static tubes	Dwyer Instruments Pitot Tube	6 in. insertion depth, 1/8 in. diameter
Differential pressure transducers	Omega Engineering PX274-02DI	0-1, 0-0.5, 0-0.25 in. w.g. selectable
RH/T transducer	Dwyer Instruments Humidity/Temperature Transmitter	10-90% RH, -40 to 140°F
Barometric pressure transducer	Omega Engineering PX409-32BV	16-32 in. Hg
Programmable Logic Controller	Allen-Bradley MicroLogix 1100	

A schematic showing the electrical and data connections among the instruments, controller, PC, VFD, and fan is provided as Figure 4.5. All of the sensors selected are two-wire (loop-powered) and provide a 4-20mA analog output. Current-output sensors provide a signal which is much less sensitive to electromagnetic interference (EMI) noise pickup in the cables and unlike voltage-output sensors, the signal integrity of analog-output sensors is not nearly as sensitive to overall cable length. Given that the sensors in this application will be installed in some cases up to 50 ft from the PLC, current-output sensors were greatly preferable to voltage-output sensors. Additionally, although not omitted from the wiring schematic for simplicity, shielded cables were used for all data connections. Proper cable shield grounding protocol, in which the cable shield is grounded only at the controller termination, was consistently followed.

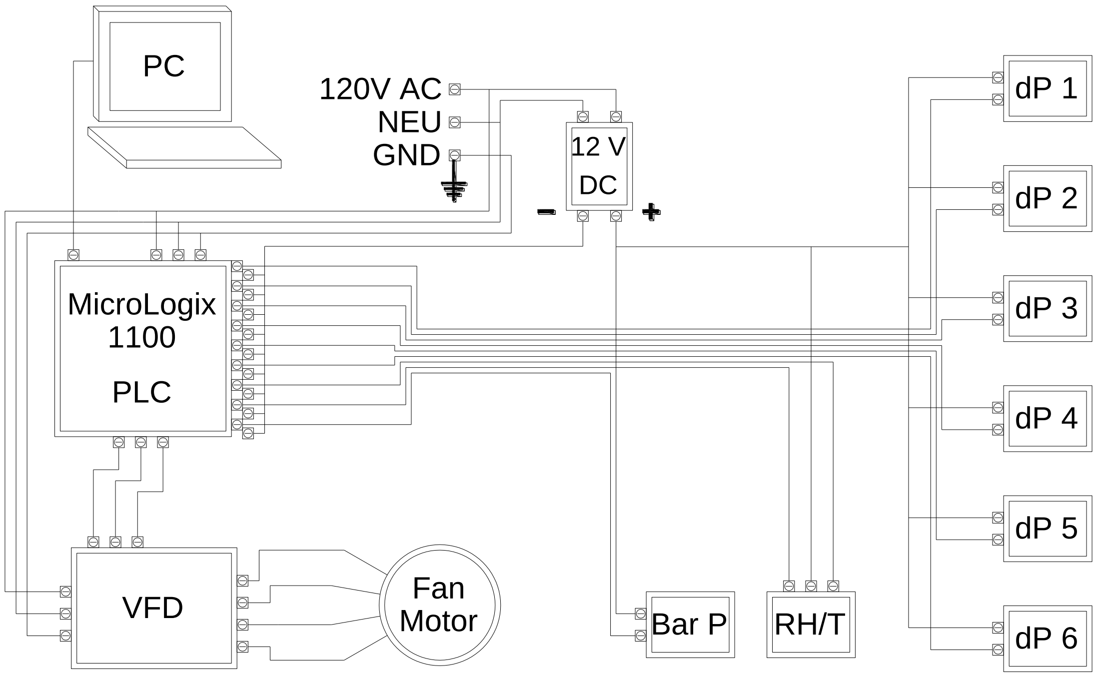

FIGURE 4.5. INSTRUMENTATION CIRCUIT DIAGRAM

4.2.1. VELOCITY AND QUANTITY MEASUREMENT

The Pitot-static tubes selected for velocity measurement are constructed from ⅛-in. O.D. stainless steel with a 6-in. insertion depth, measured from the centerline of the sensing tip to the wide section of the tube. Although the 6-in. depth means the Pitot-static tube will protrude approximately 5 in. out of the pipe, this is the smallest widely available Pitot-static tube from Dwyer Instruments. Figure 4.6 shows one of the Pitot-static tubes used for velocity measurement; a U.S. quarter coin is included for scale.

FIGURE 4.6. PITOT-STATIC TUBE SHOWING SCALE

In order to measure velocity using a Pitot-static tube, the pressure difference between total (stagnation) pressure and static pressure is measured. A wide variety of manometers and pressure transducers, based on several physical phenomena, are available to measure differential pressure. Applying Eq. (2.8), the velocity pressure for various air velocities can be estimated. A plot of estimated velocity pressure vs. air velocity assuming standard air density is provided as Figure 4.7. From this plot it can be show that for velocities less than about 2800 fpm, a velocity pressure of less than 0.5 in. w.g. will be measured. For this application, a PX274-02DI low pressure transducer was selected from Omega Engineering; this pressure transducer has user-selectable ranges of 0-1, 0.-0.5, and 0-0.25 in. w.g., making it appropriate for the range of pressure measurements expected in the experimental apparatus using Pitot-static tube anemometry.

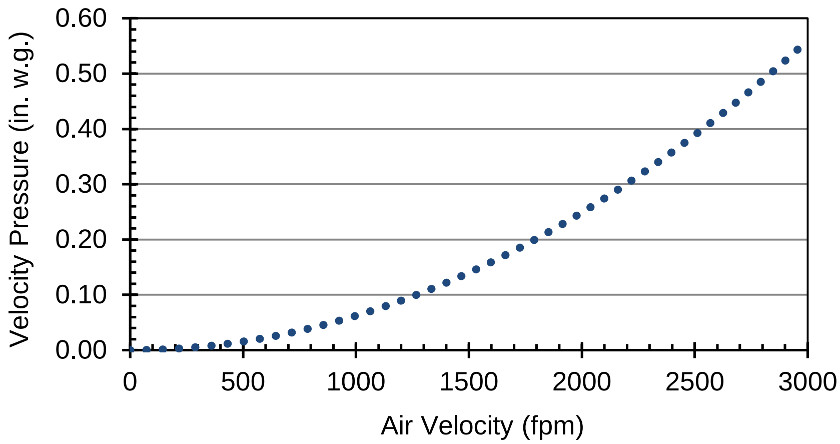

FIGURE 4.7. PLOT OF VELOCITY PRESSURE VS. AIR VELOCITY

The differential pressure transducers selected are packaged in NEMA-12 rated enclosures and are mounted with bolts onto a steel strut above the experimental apparatus, as pictured in Figure 4.8. Pressure tubes, made from 3/16-in.-diameter Tygon tubing, were used to connect the high (total) and low (static) pressure ports from the Pitot-static tube to the corresponding ports on the differential pressure transducer. The pressure tubes were attached to the smooth Pitot-static tube pressure ports using heat-shrink polyolefin tubing to ensure an airtight seal and were cable-tied together for neatness. Figure 4.9 shows a Pitot-static tube attached to a differential pressure transducer at one of the velocity measuring points on the apparatus.

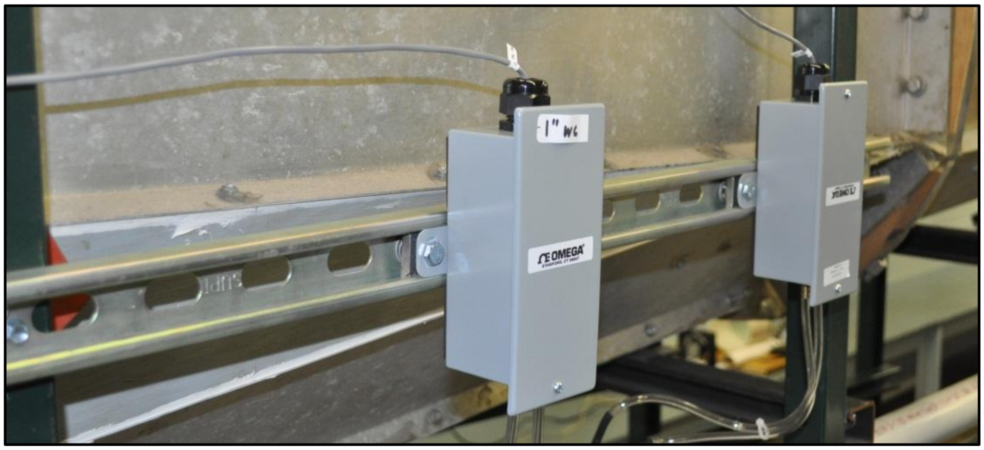

FIGURE 4.8. DIFFERENTIAL PRESSURE TRANSDUCERS MOUNTED TO STEEL STRUT

FIGURE 4.9. DIFFERENTIAL PRESSURE TRANSDUCER, CONNECTED TO PITOT-STATIC TUBE VIA TYGON PRESSURE TUBING

The Pitot-static tube is arranged such that the sensing tip is in the center of the airway. Given that the velocity at the center of the airway is not the average velocity (recall, the fully-developed velocity profile across a conduit is parabolic), the application of a correction factor from literature is necessary to convert the centerline velocity into the average velocity [60]. The formula for this conversion, given as

$$V_{avg} = 0.85V_{center} \qquad \text{Eq. (4.1)}$$

is applied in all calculations in which quantity is calculated from measured centerline velocity.

4.2.2. RELATIVE HUMIDITY, TEMPERATURE AND BAROMETRIC PRESSURE

In order to achieve more accurate velocity measurements using Pitot-static tubes, the velocity calculations should be corrected for current air density. Three parameters are needed to calculate air density in real time; these are temperature, barometric pressure and relative humidity (or the partial pressure of water vapor). Most important in calculating the air density are the air temperature and barometric pressure. The accuracy of this can be increased incrementally by factoring in the contribution of water vapor to air density. As far as sensing technology applies, temperature and relative humidity are both commonly collected data for HVAC systems, while quality barometric pressure transducers and generally comparably expensive. For the experimental apparatus, a simple combination relative humidity (RH) and temperature sensor (RH/T sensor) was purchased. This sensor package from Dwyer Instruments was available in a simple plastic enclosure designed for wall-mounting, as shown in Figure 4.10. The ranges for both temperature and relative humidity far exceed those likely to occur in the climate-controlled lab, so a costly sensor package was deemed inappropriate. For barometric pressure measurement, a PX-409 barometric pressure transducer configured for 24V DC excitation, 16-32 in. Hg measurement range and 4-20mA analog output was purchased from Omega Engineering. The barometric pressure transducer is shown in Figure 4.11.

FIGURE 4.10. RELATIVE HUMIDITY/
TEMPERATURE SENSOR (WALL-MOUNT HOUSING)

FIGURE 4.11. BAROMETRIC PRESSURE TRANSDUCER

4.2.3. PROGRAMMABLE LOGIC CONTROLLER

As an interface between the PC and the sensors and fan control, a programmable logic controller (PLC) was selected. A PLC was selected because it is modular, versatile, and simple to program. A PLC can perform the multiple roles of data acquisition, digital switching, and analog and digital control. The PLC selected is an Allen-Bradley MicroLogix 1100, a compact logic controller with embedded analog and digital I/O (relays), an embedded LCD screen error-reading and an embedded web server with the capability for webhosting and online editing. The MicroLogix 1100 can be expanded with up to four 1762-I/O Modules, of which four appropriate modules were also selected. Many of the relevant technical specification are included in the section Appendix: Selected Technical Specifications. Three analog input modules were selected to monitor the sensor inputs. One analog output module was also selected for analog control of future devices, such as variable speed fans. The PLC and expansion I/O modules are shown as installed in Figure 4.12.

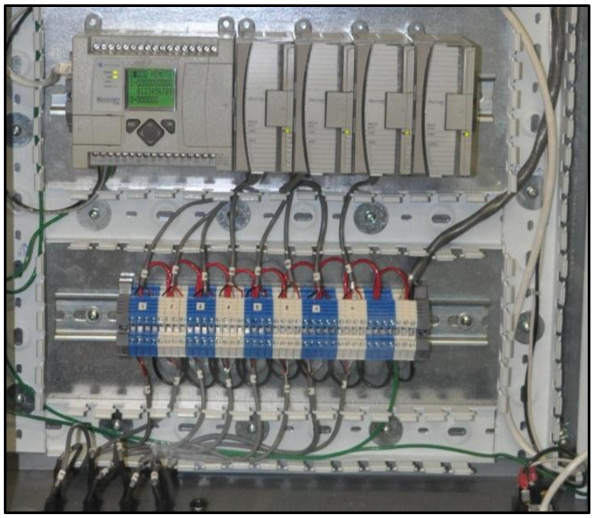

FIGURE 4.12. MICROLOGIX 1100 PLC WITH THREE ANALOG INPUT MODULES, ONE ANALOG OUTPUT MODULE AND DATA CONNECTIONS

The PLC was programmed from the PC in the ventilation lab using Rockwell Automation's RSLogix500 software package. Another program from Rockwell Automation, RSView32, was used to create a simple display for the sensor output. Experimenters can quickly record velocities from up to six locations in the apparatus where the Pitot-static tubes are present and view the current air temperature, barometric pressure and relative humidity from the computer screen. A screenshot of the display is provided as Figure 4.13. Screenshots of the ladder logic used for the instrumentation are provided as Appendix B.

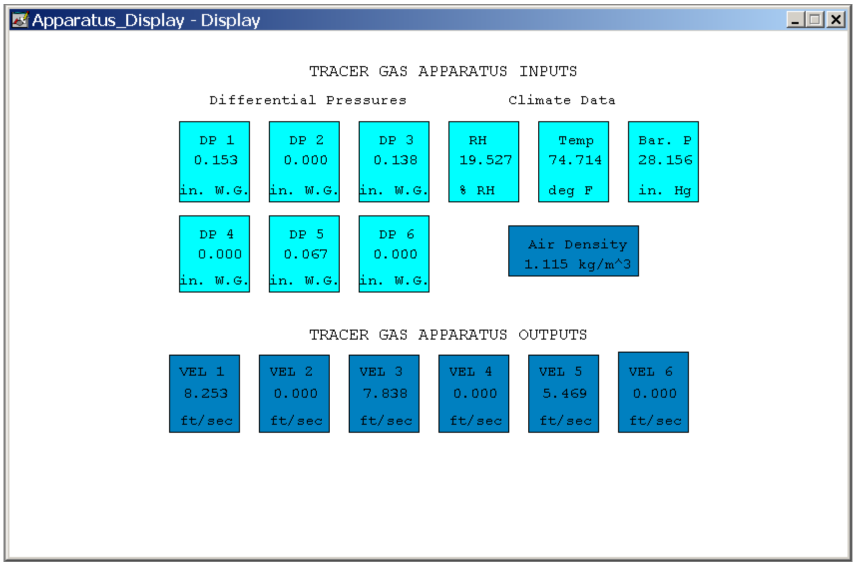

FIGURE 4.13. SCREENSHOT OF THE APPARATUS GUI DISPLAY

4.2.4. ENCLOSURE AND POWER SUPPLY

In order to house the controller, power supply, circuit breakers and power distribution, a 24 in. × 20 in. × 8in. NEMA-12 rated enclosure was selected. The enclosure selected has a window in the door to enable the user to check the status of the controller without compromising the electrical insulation by opening the door. All electrical components which would be in the housing were those which would mount to a 35mm O-type DIN-rail, a standard mounting rail for industrial control equipment. Three DIN-rails were mounted horizontally to the enclosure backplane with self-tapping metal screws. Cable channel was mounted to the backplane between, above, below and to both sides of the DIN-rails for cable management. Figure 4.14 shows the enclosure backplane with the PLC and analog I/O modules, circuit breakers, power supply, and terminal blocks mounted to the DIN-rails.

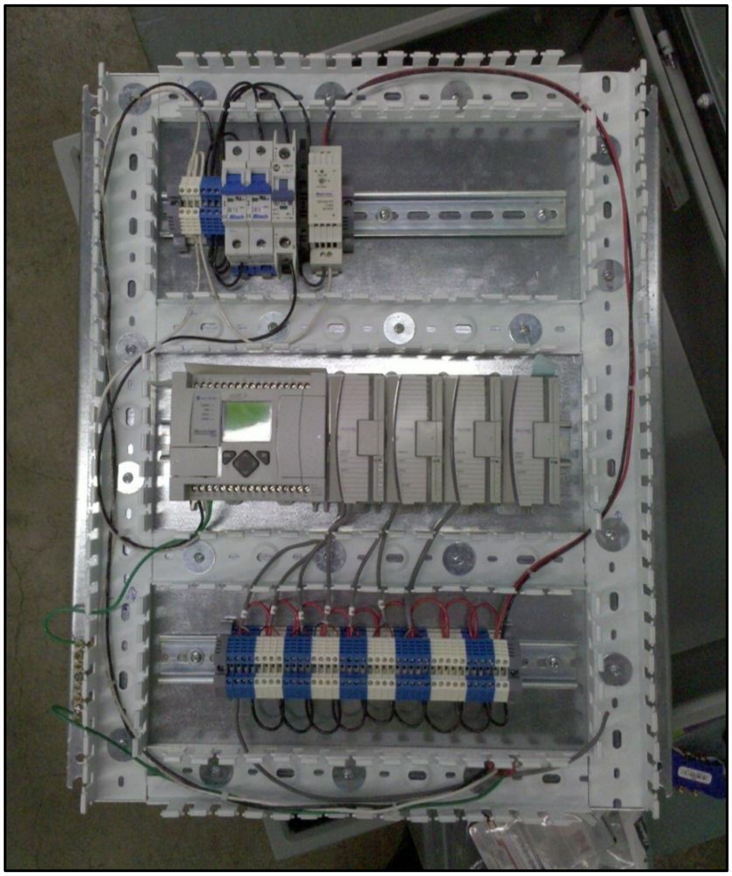

FIGURE 4.14. BACKPLANE WITH PLC, CIRCUIT BREAKERS, 24V DC POWER SUPPLY AND TERMINAL BLOCKS

The enclosure was mounted to the wall in one corner of the ventilation lab and the backplane was attached inside. Female connections for 120V AC power, data (4-pin mini DIN) and communications (Ethernet and D-sub 9) cables were all installed through the bottom of the enclosure. For each of the sensors (pressure transducers and RH/T sensor), a length of shielded cable was attached to the sensor package and terminated in a soldered male 4-pin mini DIN connector. The 9-pin D-sub connector was installed later for communication and control connection to the variable frequency drive (VFD) chosen to provide power for the upgraded fan, described later. A photo of the enclosure as installed is included as Figure 4.15.

FIGURE 4.15. ELECTRICAL ENCLOSURE WITH ALL CONNECTIONS COMPLETED

All of the sensors were selected to be 2-wire, 4-20 mA analog output, 24V DC loop-powered sensors. One 15W 24V DC power supply from Altech Corp. was selected to power the instrumentation. Summing the potential current draw of all available sensors (20 mA per sensor output), a total current source of less than 200 mA (0.20 A) was required for all the instrumentation. A summary of the current draw for the sensors is provided as Table 4-2. Specifications of the power supply selected are provided in Appendix A.

TABLE 4-2: CURRENT CALCULATIONS FOR POWER SUPPLY SELECTION

Device	Full-scale current	No. of Devices	Total Draw
Barometric pressure transducer	20 mA	1	20 mA
Differential pressure transducer	20 mA	6	120 mA
RH/T transducer	40 mA	1	40 mA
Total	**-**	**8**	**180 mA**

4.2.5. Calibration of instruments

Calibration of the instruments is important for accurate velocity/quantity measurement. The barometric pressure transducer was purchased with a National Institute of Standards and Technology (NIST)-traceable certificate of calibration. Provided with this certificate are five calibration points which should be used to correct the analog output of the transducer for accurate measurement. The other transducers were not provided with NIST-traceable calibrations, though they are factory calibrated to meet or exceed the published specifications of the instrument. Those published specifications are provided among the technical specifications of the instruments included in Appendix A. Calibration instructions are provided with the low-pressure transducers should field adjustment be necessary. The RH/temperature transducer cannot be field calibrated.

4.3. Initial performance and improvements/modifications

4.3.1. Fan upgrade

After the initial construction was completed, some preliminary experiments were conducted. It was noted that the small centrifugal fan first used for the apparatus produced a fairly low quantity, with air velocities in the split sections only just above the critical velocities for turbulence. As future mine model geometries will be more complex and larger, a fan was needed which could supply a minimum quantity to potentially several parallel branches and at higher resistance. A PW-9 8-in. radial fan was purchased from Grainger which could be driven by a ½-hp motor using a variable frequency drive (VFD). As stated in section 3.4 on similitude, velocities in the range of 8 m/s (26 ft/sec) in the parallel branches were measured, well above the critical velocity for turbulent flow, calculated to be roughly 1.2 m/s (4 ft/sec). Given that the Reynolds number similitude criterion was satisfied and the Reynolds number is well into the turbulent range, the new fan was an appropriate choice. The new fan, shown in Figure 4.16, is much larger and heavier than the original fan without housing shown in Figure 4.4. The new ½-hp fan was permanently mounted to a platform at one end of the apparatus and 3-

in.-diameter PVC pipe was run from its outlet directly outside the building, maintaining the airtightness required by the experimental goals.

FIGURE 4.16. A 1/2-HP BLOWER FAN WAS SELECTED TO REPLACE THE SMALLER CENTRIFUGAL FAN

4.3.2. VARIABLE FREQUENCY DRIVE

The ½-hp-rated Baldor VS1MX10P5-2 VFD selected as the motor drive is shown in Figure 4.17. The VFD transforms 115V 60 Hz single-phase AC power into 230V three-phase AC power at a controllable frequency; the speed of an AC electric motor is directly proportional to the drive frequency. This VFD allows the user to vary the air velocity in the apparatus, which may be useful in experiments to set up specific conditions. The VFD selected has both a relay control, which is included as a safety interrupt and must be closed for the drive to run, and an analog input for speed. These features allow the drive to be hardwired to an on/off switch and a speed control knob (trim potentiometer) or, as with this apparatus, controlled by a logic controller. Using the analog input, connected with the analog output module of the PLC, the user can set a desired air velocity at a specific location. The fan speed could then be adjusted by the PLC until the target velocity is reached.

FIGURE 4.17. VARIABLE FREQUENCY DRIVE

4.3.3. PERFORMANCE CHARACTERISTICS OF THE NEW FAN AND VFD

The upgraded fan powered via VFD easily provides the required air velocity to maintain turbulent flow throughout the apparatus. The critical Reynolds number for turbulent flow can be calculated using measured laboratory conditions. Using the air density and pipe diameter measured in the lab and viscosity from tables,

$$\rho_{air(lab)} = 1.103 \text{ kg/m}^3$$
$$\mu_{air} = 1.79 \times 10^{-5} \text{ N·s/m}^2$$
$$D_{pipe} = 0.0508 \text{ m} ,$$

and recalling the critical Reynolds number for turbulent flow and the definition of the Reynolds number,

$$\text{Re}_{crit} = 4000$$
$$\text{Re} = \frac{\rho V D}{\mu}$$

one can calculate the critical velocity V_{crit} above which flow is turbulent

$$V_{crit} = \frac{\mathrm{Re}_{crit} \cdot \mu}{\rho \cdot D} = \frac{4000(1.79 \times 10^{-5}\ \mathrm{N{\cdot}s/m^2})}{(1.103\ \mathrm{kg/m^3})(0.0508\ \mathrm{m})} \qquad \text{Eq. (4.2)}$$

$$V_{crit} = 1.28\ \mathrm{m/s}.$$

At Point 1, the measurement point in the inlet airway, the air velocities were measured as a function of fan speed. These velocities, measured over what should be considered the normal operating range of the fan, are displayed in Figure 4.18. Although the fan could theoretically be operated at speeds approaching zero RPM, practical limitations (primarily the current draw in the VFD) establish a lower limit. For this reason, the practical operating range of the fan should always produce air velocities above the critical air velocity of 1.28 m/s. This is the velocity in the inlet, so should the air split into several airways, it can still be maintained above the critical velocity. A plot of the fan speed as a function of the motor frequency is provided as Figure 4.19. Operating the fan for extended periods outside its designed operating range can shorten its life, so caution is taken keep the motor frequency below 120 Hz (twice the design speed). Though the upper limit of the VFD output is 5000 Hz, operating the fan at much higher speeds could tend to damage the fan more quickly and should be avoided. Using the quantities, computed via Eq. (2.1) by applying the correction factor in Eq. (4.1), the characteristic curve of the apparatus was also computed. The characteristic curve, which shows the pressure drop over the apparatus as a function of the quantity forced through it, is provided as Figure 4.20. Also plotted is the best-fit polynomial of power 2; recalling Eq. (2.4), the head loss of an airway or network sum of airways is understood as a function of the square of quantity. Using the characteristic curve, the equivalent resistance of the apparatus can be calculated

$$R_{apparatus} = \frac{H_{friction}}{Q^2} = \frac{(1.08\ \text{in. w.g.})}{(28.2\ \text{cfm})^2} \qquad \text{Eq. (4.3)}$$

$$R_{apparatus} = 0.00146\ \text{in. w. g./cfm}^2.$$

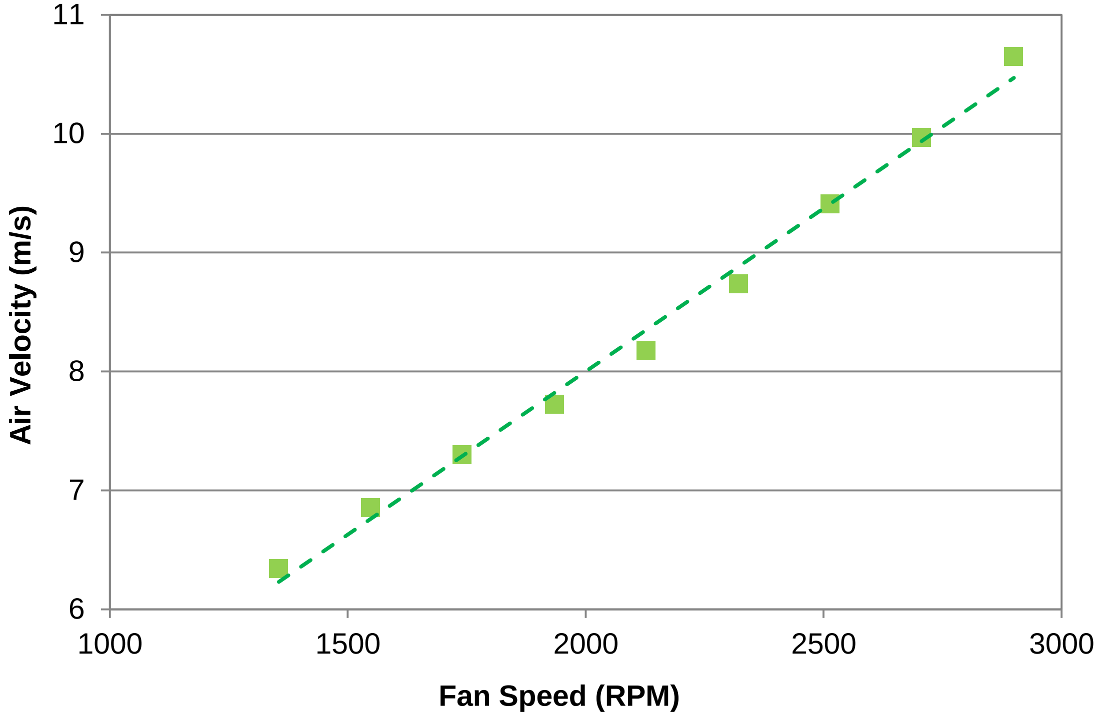

FIGURE 4.18. PLOT OF AIR VELOCITY (BEYOND INLET) VS. FAN SPEED OVER NORMAL OPERATING RANGE

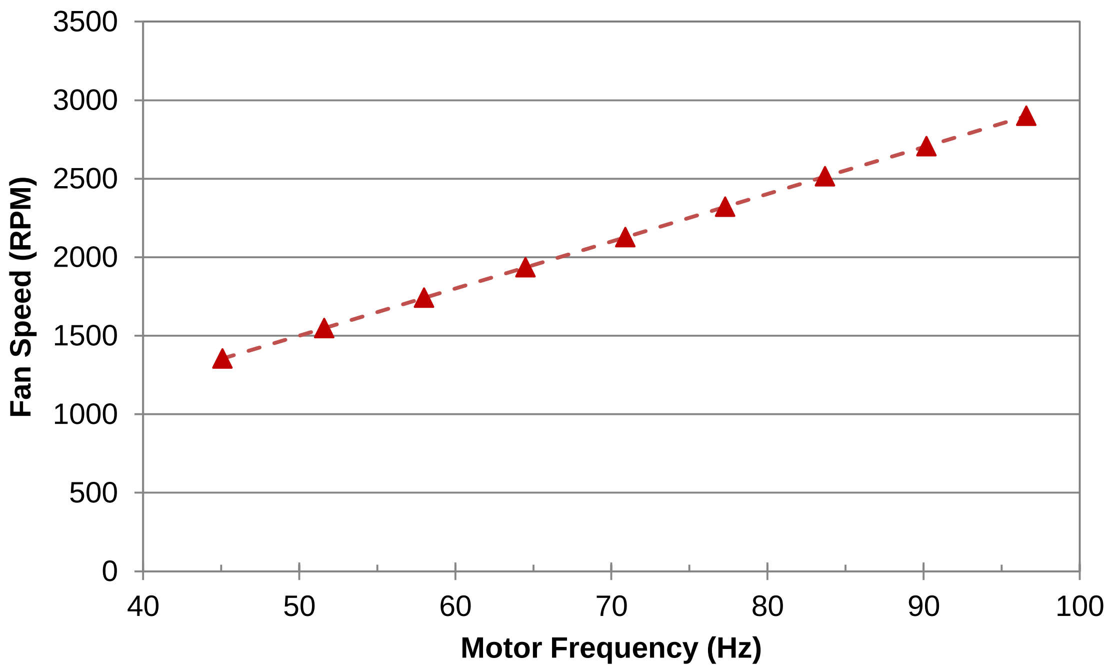

FIGURE 4.19. PLOT OF FAN SPEED VS. MOTOR FREQUENCY

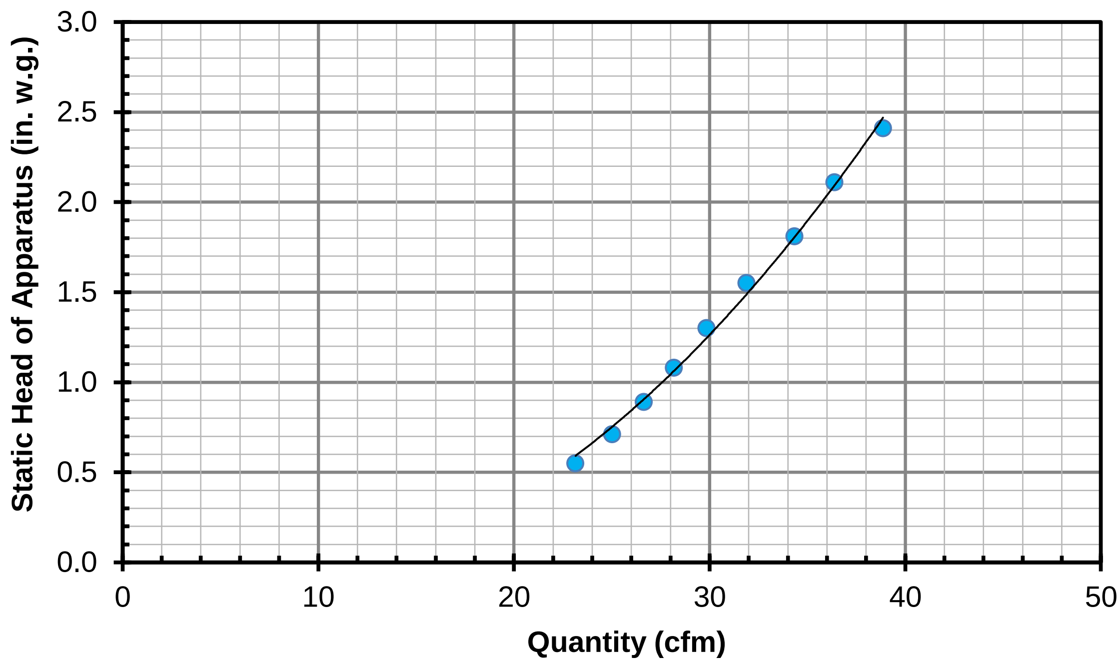

FIGURE 4.20. PLOT OF CHARACTERISTIC CURVE OF APPARATUS

4.4. COST OF APPARATUS

The total cost of the apparatus was approximately $5000. Much of the cost was associated with instrumentation, with pressure transducers and the PLC representing the bulk of the instrumentation cost. In general, the accuracy of an instrument is a primary factor in its cost; the robustness of the enclosure, warranty, calibration and other features also contribute to the cost. Another large portion of the cost was made up by the fan, ½-hp motor and VFD, which were purchased as later improvements to the system. Academic discounts from generous suppliers reduced the costs of the PLC and associated programming software, the electrical enclosure and the pressure transducers. A summary of the costs of major components of the experimental apparatus is included in Appendix C.

5. Summary and Conclusions

5.1. Summary of project

An experimental apparatus was constructed which will be used to conduct tracer gas experiments in the laboratory. The test apparatus is modular and simple and can be easily rearranged to represent a variety of mine geometries. The apparatus is appropriate for the use of tracer gases by being both airtight and open-circuit (exhausting to the atmosphere) and by maintaining a turbulent flow regime throughout the model. The test apparatus simulates a mine in a tabular deposit by being topologically identical to a simple longwall mine and by demonstrating similitude with a typical longwall mine with adherence to modeling theory (following the Buckingham pi theorem).

The model features ports for injection and sampling of tracer gases, which represent boreholes in the mine prototype. The sampling/injection ports can be pierced with a syringe or solid-phase microextraction (SPME) fiber so that many of the methods for the release and sampling of tracer gases can be practiced in the laboratory, albeit on a smaller scale and in a more controlled environment. Valves on the apparatus represent ventilation controls, such as stoppings or regulators, or changing resistances in a mine, such an increase in resistance due to a roof fall or a decrease in resistance due to stoppings being destroyed. The relative resistances of airways can be changed by changing the status of the valves to represent different states of the ventilation controls.

The model, which is simple and versatile, can be used to represent a working mine ventilation system for the purpose of tracer gas sampling. A wide variety of mine plans can be simulated by reconstructing the modular model into different geometries. Once a particular model geometry has been established, various ventilation states should be identified. By performing tracer gas tests in the model under “normal” ventilation operating conditions, baseline tracer gas profiles can be constructed. Researchers should then apply changes to the state of ventilation controls in the model by adjusting the airway resistances using the valves. Performing tracer gas tests after changes have been made to the ventilation network, the tracer gas profiles can be compared to infer the nature of the changes from the normal ventilation conditions. The mine simulator described in this paper is meant to help researchers develop a method for inferring ventilation changes remotely using tracer gases.

5.2. Conclusions

Four criteria were determined which the apparatus should meet to be considered successful for the purposes of tracer gas experimentation. The experimental apparatus for tracer gas investigation should

1) simulate a mine in a tabular deposit,
2) allow for the injection and sampling of appropriate amounts of tracer gases,
3) simulate changes in ventilation (as after a mine disaster) by incorporating simple variable ventilation controls, and
4) allow for the measurement and monitoring of air velocities (quantities) and atmospheric conditions (temperature, relative humidity and barometric pressure) within the apparatus.

The apparatus meets the goals, as described above, via the following.

1) The apparatus is topologically identical to and demonstrates similitude with a simplified longwall coal mine. Turbulent flow is maintained in the apparatus.
2) The apparatus has ports through which chemical tracer gases can be injected and sampled while maintaining an airtight seal to prevent leaks into the laboratory atmosphere. The apparatus allows for precise measurement of tracer gases, as shown in initial experiments [84].
3) The apparatus contains several valves at key locations which can be used as ventilation controls. They can be opened or closed to represent the type of damage which might occur in a mine disaster, such as a roof fall or explosion.
4) The apparatus is instrumented with velocity and climate measurement devices. Instruments measure temperature, relative humidity and barometric pressure to compute air density and the air density is used to correct air velocity measurements, made at each sampling/injection port.

5.3. Future work

For the future use of the apparatus, some suggestions are presented for the improvement of the apparatus as a research tool. One such improvement which would be beneficial is the replacement of the opaque PVC pipe at the sampling/injection ports with a transparent pipe, such as a pipe constructed from Lexan or a similar transparent plastic. This pipe could also be fitted with a depth gauge for measuring the protrusion depth of the Pitot-static tube and sampling instrument in the airway. The Pitot-static tube could then be inserted at various depths into the airway and the velocity at each depth could be measured in order to define the velocity profile across a section of the duct. The velocity profile could be compared among sampling/injection ports to determine whether the flow at each sampling/injection port section is fully-developed. Additionally, accurately defining the velocity profile across the duct could also assist in determining the average velocity in the airway as a function of the insertion depth of the Pitot-static tube, rather than by applying a literature-value coefficient for velocity measured along the centerline.

The depth gauge, readable through the transparent pipe, would also assist in reliably sampling from precisely the same point or points in the airflow. In an actual mine airway, a mine ventilation engineer would establish a regular sampling pattern likely consisting of sampling either the center of the airway or sampling over a specific traverse of the airway. Similarly, the researcher sampling the air in the model could draw samples from the same depth in the airway each time, with the aim of establishing a similar protocol for repeatability.

In order to define a tracer gas profile from a slug test, several samples must be drawn over the time in which the slug passes the sampling point. Plotting the concentrations of those samples, a tracer gas concentration profile can be created. In a slug test, a tracer gas profile under given ventilation conditions is observed and can be compared with the profile under different conditions to draw conclusions about the ventilation control changes. Currently, the residence time of a slug (fixed volume) of tracer gas in the apparatus is too short for measurement using typical slug test techniques.

In its current form and with the operating velocities described, a tracer gas slug takes less than five seconds to pass from the inlet to the exhaust of the apparatus. With a minimum practical sampling frequency of approximately two seconds, the concentration cannot be plotted with enough resolution to accurately define the tracer profile. In order to provide a longer residence time for tracer gas slug tests, the apparatus should be extended in length and the air velocity should be slowed (while still maintaining highly turbulent flow conditions for good mixing).

Another upgrade which should be added to the apparatus is an electronic mass-flow controller. More accurate measurements of the injection rate of SF_6 and other tracers could improve the accuracy of experimental results. The PLC should be used to initiate the flow of gas into the apparatus so that its release rate and time can be precisely controlled. The experimenter could also set a delay and a visual or audio cue to begin sampling from the apparatus when the mass-flow controller begins injecting gas into the apparatus.

Using this experimental mine simulator, researchers will seek to develop standardized tracer gas release and sampling procedures with which multiple tracer gases can be used simultaneously. If the method of tracer gas inference is proven successful in laboratory studies, it is hoped that the method can be scaled up and applied to operating mine ventilation networks. Following the development of standardized tracer gas release and sampling procedures, tracer gas surveys should be conducted in actual mines before and after changes are made to the ventilation network and researchers will try to correlate changes in the tracer profiles to changes in the mine ventilation network. This technique could ultimately allow mine engineers to conduct a tracer gas survey following a disaster in which unknown changes occurred in the mine ventilation network and, by comparing the tracer gas profiles to the baseline normal operating profiles, infer the nature of changes in the ventilation network. This would allow for more rapid assessment of the ventilation conditions following a disaster and, in the case of a rescue operation, help to better inform mine rescue teams earlier about the status of the mine ventilation.

REFERENCES

[1] E.D. Thimons, R.J. Bielicki, and F.N. Kissell, *Using sulfur hexafluoride as a gaseous tracer to study ventilation systems in mines*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1974.

[2] E.D. Thimons and F.N. Kissell, *Tracer Gas as an Aid in Mine Ventilation Analysis*, Pittsburgh, PA: U.S. Bureau of Mines, Washington, DC (USA), 1974.

[3] B.E. Saltzman, A.E. Coleman, and C.A. Clemens, "Halogenated Compounds as Gaseous Meteorological Tracers," *Analytical Chemistry*, vol. 38, 1966, pp. 753-758.

[4] L.E. Niemeyer and R.A. McCormick, "Some Results of Multiple-Tracer Diffusion Experiments at Cincinnati," *Journal of the Air Pollution Control Association*, vol. 10, 1968, pp. 403-405.

[5] R. Lalauze, *Physical Chemistry of Solid-Gas Interfaces: Concepts and Methodology for Gas Sensor Development*, Hoboken, NJ: John Wiley & Sons Inc., 2008.

[6] J. Keller and R. Staudt, *Gas Adsorption Equilibria: Experimental Methods and Adsorption Isotherms*, New York: Springer Science+Business Media Inc., 2005.

[7] W.A. Steele, "The Interaction of Gases with Solid Surfaces," *The International Encyclopedia of Physical Chemistry and Chemical Physics*, 1974, p. 349.

[8] C.A. Clemens, A.I. Coleman, and B.E. Saltzman, "Concentration and Ultrasensitive Chromatographic Determination of Sulfur Hexafluoride for Application in Meteorological Tracing," *Environmental Science and Technology*, vol. 2, 1968, pp. 551-556.

[9] G.F. Collins, F.E. Rartlett, A. Turk, S.M. Edmonds, and H.L. Mark, "A Preliminary Evaluation of Gas Air Tracers," *Journal of the Air Pollution Control Association*, vol. 15, 1965, pp. 109-112.

[10] A. Turk, S.M. Edmonds, H.L. Mark, and G.F. Collins, "Sulfur Hexafluoride as a Gas-Air Tracer," *Environmental Science and Technology*, vol. 2, 1968, pp. 44-48.

[11] P.J. Drivas, P.G. Simmonds, and F.H. Shair, "Experimental Characterization of Ventilation Systems in Buildings," *Environmental Science and Technology*, vol. 6, 1972, pp. 609-614.

[12] N. Foord and O.M. Lidwell, "A method for studying air movement in complex occupied buildings such as hospitals: halocarbons as gas tracers using gas chromatography," *Building Services Engineer*, vol. 41, 1973, pp. 93-100.

[13] D. Lester and L.A. Greenberg, "The Toxicity of Sulfur Hexafluoride," *Archives of Industrial Hygiene and Occupational Medicine*, vol. 2, 1950, pp. 348-349.

[14] J. Higgins and S.E.H. Shuttleworth, “A Tracer Gas Technique for the Measurement of Airflow in Headings,” *Colliery Engineering*, vol. 35, 1958, pp. 483-487.

[15] G.E. Rennick, J.I. Pasini, F.E. Armstrong, and J.R. Abrams, *Demonstration of Safety Plugging of Oil Wells Penetrating Appalachian Coal Mines*, Bureau of Mines, Washington, DC (USA), 1972.

[16] F.N. Kissell and R.J. Bielicki, *Ventilation Eddy Zones at a Model Coal Mine Working Face*, Pittsburgh, PA: 1974.

[17] F.N. Kissell and R.J. Bielicki, *Methane Buildup Hazards Caused by Dust Scrubber Recirculation at Coal Mine Working Faces, A Preliminary Estimate*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1975.

[18] R.P. Vinson and F.N. Kissell, *Three coal mine ventilation studies using sulfur hexafluoride tracer gas*, Pittsburgh, PA: US Dept. of the Interior, Bureau of Mines, 1976.

[19] J.E. Matta, S.D. Maksimovic, and F.N. Kissell, *Tracer Gas Method for Measuring Leakage Through Mine Stoppings*, Pittsburgh, PA: US Dept. of the Interior, Bureau of Mines, 1978.

[20] R.P. Vinson, E.D. Thimons, and F.N. Kissell, *Brattice Window Method for Measuring Leakage Through Mine Stoppings*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1977.

[21] J.E. Matta, E.D. Thimons, and F.N. Kissell, *Jet Fan Effectiveness as Measured With SF 6 Tracer Gas*, Pittsburgh, PA: US Dept. of the Interior, Bureau of Mines, 1978.

[22] R.J. Timko and E.D. Thimons, *Sulfur hexafluoride as a mine ventilation research tool-Recent field applications*, Washington, DC (USA): 1982.

[23] R.P. Vinson, F.N. Kissell, J.C. LaScola, and E.D. Thimons, *Face Ventilation Measurement with Sulfur Hexafluoride (SF6)*, Bureau of Mines, Washington, DC (USA), 1980.

[24] R.J. Timko, F.N. Kissell, and E.D. Thimons, “Evaluating Ventilation Parameters of Three Coal Mine Gobs,” *Proceedings of The 3rd Mine Ventilation Symposium*, 1983, p. 11.

[25] J.C. Volkwein, S.K. Ruggieri, C. McGlothlin, and F.N. Kissell, *Exhaust Ventilation of Deep Cuts Using a Continuous-Mining Machine*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1985.

[26] R.J. Timko and R.L. Derick, “Determining the Integrity of Escapeways During a Simulated Fire in an Underground Coal Mine,” *Proceedings of the 4th US Mine Ventilation Symposium*, 1988, pp. 48-56.

[27] R.P. Vinson, J.C. Volkwein, and E.D. Thimons, *SF6 Tracer Gas Tests of Bagging-Machine Hood Enclosures*, Pittsburgh, PA: US Dept. of the Interior, Bureau of Mines, 1981.

[28] S.G. Hardcastle and A. Sheikh, "Evaluation Of The Air Quality And Distribution During The Rest Period Of Bacterially Assisted Leaching Operations In Uranium Mines," *Proceedings of the 3rd Mine Ventilation Symposium*, 1986, pp. 343-352.

[29] E.D. Thimons, C.E. Brechtel, M.E. Adams, and J.F.T. Agapito, *Performance Characteristics of Large-Capacity Face Ventilation Systems for Oil Shale Mining*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1986.

[30] E.D. Thimons and C.E. Brechtel, "Measurement and Simulation of Face Ventilation Effectiveness for Large Diesel Powered Equipment," *3rd Mine Ventilation Symposium*, 1987, pp. 273-278.

[31] M.E. Adams, C.E. Brechtel, J.F.T. Agapito, and E.D. Thimons, "Leakage Testing Of Large Ventilation Control Structures For Room And Pillar Oil Shale Mining," *Proceedings of The 3rd Mine Ventilation Symposium*, 1987, pp. 365-370.

[32] W.J. Fisk, J. Binenboym, H. Kaboli, D.T. Grimsrud, A.W. Robb, and B.J. Weber, "A Multi-Tracer System for Measuring Ventilation Rates and Ventilation Efficiencies in Large Mechanically-Ventilated Buildings," *AIC 6th Conference Ventilation Strategies and Measurement Techniques*, Het Meerdal Park, Netherlands: 1985, pp. 69-92.

[33] P.L. Lagus, V. Kluge, P. Woods, and J. Pearson, "Tracer Gas Testing Within the Palo Verde Nuclear Generating Station Unit 3 Auxiliary Building," *20th DOE/NRD Nuclear Air Cleaning Conference*, 1988, pp. 430-456.

[34] R.A. Grot and P.L. Lagus, "Application of Tracer Gas Analysis to Industrial Hygiene Investigations," *Industrial Hygiene News, May 1991*, 1991, p. 21.

[35] R.A. Grot and P.L. Lagus, "The Evaluation of Ventilation Systems Using Tracer Gas Methods," *Industrial Hygiene News, July 1991*, 1991, p. 34.

[36] P.L. Lagus and R.A. Grot, "Airborne Hazardous Substance Assessment By Tracer Gas Methods," *Industrial Hygiene News, Sept. 1991*, 1991, pp. 1-22.

[37] R.A. Grot and P.L. Lagus, "Airflow and Contaminant Migration Modeling," *Industrial Hygiene News, December 1991*, 1991, pp. 1-18.

[38] R.A. Grot and P.L. Lagus, *Application of tracer gas analysis to industrial hygiene investigations*, 1991.

[39] D.J. Kennedy, A.W. Stokes, and W.G. Klinowski, "Resolving Complex Mine Ventilation Problems with Multiple Tracer Gases," *Proceedings of The 3rd Mine Ventilation Symposium*, Sydney, Nova Scotia: 1987.

[40] W. Eraker and A.L. Mossman, *Gas Data Book*, Matheson Gas Products, 1980.

[41] D.J. Kennedy, *An Analytical Method for Determining Trace Levels of Sulfur Hexafluoride and Bromotrifluoromethane and Dichlorodifluoromethane in Mine Air Samples*, 1987.

[42] W. Klinowski and D.J. Kennedy, “Tracer Gas Techniques Used in Mine Ventilation,” *Proceedings of the 5th US Mine Ventilation Symposium*, Sydney, Nova Scotia: 1991, pp. 1-5.

[43] G. Kunchur, M. Grenier, and S. Hardcastle, “Fluorspar Process Plant Dust Study,” *Proceedings of the 5th US Mine Ventilation Symposium*, 1991, pp. 667-674.

[44] A.B. Cecala, G.W. Klinowski, and E.D. Thimons, *Reducing Respirable Dust Concentrations at Mineral Processing Facilities Using Total Mill Ventilation Systems Reducing Respirable Dust Concentrations at Mineral Processing Facilities Using Total Mill Ventilation Systems*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1993.

[45] G.W. Klinowski and D.J. Kennedy, “Tracer Gas Based Evaluation of the Auxiliary Ventilation System,” *Proceedings of the 4th Mine Ventilation Symposium*, 1989, pp. 123-127.

[46] A.B. Cecala, R.J. Timko, and C.J. Pritchard, “Case Study of Controlled District Recirculation,” *Mining Engineering*, 1991, pp. 1351-1355.

[47] C.F. Meyer, “Controlled Recirculation of Mine Air in a South African Colliery,” *the 6th U.S. Mine Ventilation Symposium*, 1993.

[48] J.C. Volkwein and T.S. Wellman, “Impact of Water Sprays on Scrubber Ventilation Effectiveness,” *Proceedings of the 4th Mine Ventilation Symposium*, 1989, pp. 195-201.

[49] J.D. Potts, R.A. Jankowski, and G. Niewiadomski, *Respirable Dust Sources and Controls on Continuous Auger Mining Sections*, Pittsburgh, PA: Bureau of Mines, Washington, DC (USA), 1989.

[50] R.A. Jankowski, N.I. Jayaraman, and C.A. Babbitt, “Improved Face Ventilation Techniques Reduce Quartz Dust Levels On Continuous Mining Operations,” *Proceedings of the 4th Mine Ventilation Symposium*, 1991, pp. 181-189.

[51] G.V.R. Goodman and D.E. Pollock, “Use of a Directional Spray System Design to Control Respirable Dust and Face Gas Concentrations around a Continuous Mining Machine,” *Journal of Occupational and Environmental Hygiene*, vol. 1, 2004, pp. 806-815.

[52] J.E. Urosek and T.R. Watkins, “Gob Ventilation and Bleeder Systems in U.S. Coal Mines,” *Proceedings of the 7th US Mine Ventilation Symposium*, 1995, pp. 347-352.

[53] C. Tauzihde, Z. Pokryszka, A. Carrau, and E. Saraux, "Modeling of Gas Circulation in the Goaf of Retreat Faces," *Proceedings of the 6th International Mine Ventilation Congress*, 1997, pp. 243-246.

[54] D.A. Young, G.W. Bonnell, and D.G. Genter, "Tracer Gas Techniques for Mapping Air and Methane Migration through a Longwall Waste in an Underground Coal Mine Using Tube Bundle Systems," *SME Annual Meeting 2001*, 2001, p. 8.

[55] W.P. Diamond, S.J. Schatzel, F. Garcia, J.C. LaScola, F.E. McCall, P.W. Jeran, and T.P. Mucho, *Characterization of gas flow in longwall gobs: Pittsburgh Coalbed, PA*, Pittsburgh, PA: NIOSH, 2005.

[56] A.K. Singh, I. Ahmad, N. Sahay, N.K. Varma, and V.K. Singh, "Air leakage through underground ventilation stoppings and in situ assessment of air leakage characteristics of remote filled cement concrete plug by tracer gas technique," *The Journal of the South African Institute of Mining and Metallurgy*, 2004, pp. 101-106.

[57] G. Arpa, A. Widiatmojo, N.P. Widodo, and K. Sasaki, "Tracer gas measurement and simulation of turbulent diffusion in mine ventilation airways," *Journal of Coal Science and Engineering (China)*, vol. 14, Nov. 2008, pp. 523-529.

[58] G. Arpa, K. Sasaki, and Y. Sugai, "Narrow vein shrinkage stope ventilation measurement using tracer gas and numerical simulation," *12th U.S./North American Mine Ventilation Symposium 2008*, Wallace, eds., 2008, pp. 261-266.

[59] Y. Heritage and W. Gale, "Using Helium as a Tracer Gas to Measure Vertical Overburden Conductivity Above Extraction Panels," *Faculty of Engineering Coal Operators' Conference*, University of Wollongong, 2009, p. 10.

[60] H.L. Hartman, J.M. Mutmanksy, R.V. Ramani, and Y.J. Wang, *Mine Ventilation and Air Conditioning*, New York: John Wiley & Sons, 1997.

[61] M.J. McPherson, *Subsurface Ventilation Engineering*, Fresno, CA: Mine Ventilation Services, Inc., 2009.

[62] O. Reynolds, "An Experimental Investigation of the Circumstances Which Determine Whether the Motion of Water Shall Be Direct or Sinuous, and of the Law of Resistance in Parallel Channels," *Proceedings of the Royal Society of London*, vol. 35, Jan. 1883, pp. 84-99.

[63] O. Reynolds, "An Experimental Investigation of the Circumstances Which Determine Whether the Motion of Water Shall Be Direct or Sinuous, and of the Law of Resistance in Parallel Channels," *Philosophical Transactions of the Royal Society of London*, vol. 174, Jan. 1883, pp. 935-982.

[64] D.F. Young, B.R. Munson, T.H. Okiishi, and W.W. Huebsch, *A Brief Introduction to Fluid Mechanics*, Hoboken, NJ: John Wiley & Sons, 2007.

[65] K. Lien, J. Monty, M. Chong, and A. Ooi, “The entrance length for fully developed turbulent channel flow,” *15th Australasian Fluid Mechanics Conference (Sydney, Australia)*, 2004, pp. 1-4.

[66] R. Klopfenstein Jr., “Air Velocity and Flow Measurement Using a Pitot Tube,” *ISA Transactions*, vol. 37, Sep. 1998, pp. 257-263.

[67] D.J. Schuring, *Scale Models in Engineering: Fundamentals and Applications*, Elmsford, New York: Permagon Press Inc., 1977.

[68] J.D.J. Anderson, J. Degroote, G. Degrez, E. Dick, R. Grundmann, and J. Vierendeels, *Computational Fluid Dynamics: An Introduction*, Berlin, Germany: Springer-Verlag, 2009.

[69] W.E. Baker, P.S. Westine, and F.T. Dodge, *Similarity Methods in Engineering Dynamics: Theory and Practice of Scale Modeling*, Tokyo: Elsevier Science Publishing Company Inc., 1991.

[70] J.B. Barlow, W.H.J. Rae, and A. Pope, *Low-Speed Wind Tunnel Testing*, New York: Wiley-Interscience, 1999.

[71] R.C. Pankhurst and D.W. Holder, *Wind-Tunnel Technique: An Account of Experimental Methods in Low- and High-Speed Wind Tunnels*, London: Sir Isaac Pitman & Sons, 1952.

[72] C.E. Gregory, “The Importance of Aerodynamic Aspects,” *AIME Transactions*, 1967, pp. 214-221.

[73] B.J.A. Breslin and A.J. Strazisar, *Dust-Control Studies Using Scale Models of Coal Mine Entries and Mining Machines*, Pittsburgh, PA: U.S. Bureau of Mines, Washington, DC (USA), 1976.

[74] R.L. Stein, J.A. Breslin, and A.J. Strazisar, “Investigation of Dust Control by Ventilation Using a Scale Model,” *American Industrial Hygiene Association Journal*, vol. 35, Dec. 1974, pp. 815-824.

[75] A.D.S. Gillies, “Studies in Improvements to Coal Face Ventilation with Mining Machine Mounted Dust Scrubber Systems,” *SME-AIME Annual Meeting 1982*, 1982, p. 14.

[76] A.D.S. Gillies, “Improved Coal Face Ventilation Through the Use of Dust Scrubber Systems Leads to Greater Production Efficiency,” *Proceedings of the 1st Mine Ventilation Symposium*, 1982, pp. 43-53.

[77] J.C. Tien, “Face Ventilation During Cross-Cut Development In A Room-And-Pillar Operation,” *Proceedings of the 4th Mine Ventilation Symposium*, SME, 1989, p. 7.

[78] K. Uchino and M. Inoue, “Auxiliary Ventilation at Heading Faces by a Fan,” *Proceedings of the 6th International Mine Ventilation Congress*, 1997, pp. 493-496.

[79] I.M. Konduri, M.J. McPherson, and E. Topuz, “Simulation of Induced Jet Ventilation in a Mine Face Using a Laboratory Model,” *Proceedings of the 7th US Mine Ventilation Symposium*, 1995, p. 6.

[80] I.M. Konduri, M.J. McPherson, and E. Topuz, “Model and field investigations of jet fans for face ventilation,” *SME Transactions Volume 302*, 1997, p. 5.

[81] I.M. Konduri, M.J. McPherson, and E. Topuz, “Experimental and Numerical Modeling of Jet Fans for Auxiliary Ventilation in Mines,” *Proceedings of the 6th International Mine Ventilation Symposium*, 1997, pp. 505-510.

[82] A.D. Jones, S. Lowrie, and J. Edwards, “Aerodynamic Scale Model Simulations to Investigate the Consequences of Changes in Mining Conditions for Gas Control,” *Proceedings of the 7th US Mine Ventilation Symposium*, 1995, pp. 287-292.

[83] A.D. Jones, Z. Pokryszka, S. Lowrie, C. Tauziede, and P.-M. Dupond, “A Physical Scale Model of Flows in the Waste of a Retreat Longwall Coalface,” *Proceedings of the 6th International Mine Ventilation Congress*, 1997, pp. 231-236.

[84] G. Xu, J. Bowling, K. Luxbacher, and S. Ragab, “Computational Fluid Dynamics Simulations and Experimental Validation of Tracer Gas Distribution in an Experimental Underground Mine,” *SME Annual Meeting 2011*, 2011, pp. 1-5.

A. Appendix: Selected Technical Specifications

Table A-1: Features of the Omega PX-02DI low pressure transducer

Parameter	Value/Note
Pressure range	0-1.0 / 0-0.5 / 0-0.25 in. w.g. (DIP switch selected)
Pressure coupling	1/4-in. barb
Supply voltage	12 - 40 VDC
Accuracy*	±1% FS
Supply current	20 mA max
Output type	4 – 20 mA
Enclosure	18 Ga. C.R. steel NEMA-4
Impedance	1.6kΩ max. at 40 VDC
Dimensions	125mm × 80mm × 55mm (enclosure)
*Includes nonlinearity, hysteresis, and non-repeatability	

Table A-2: Features of the Dwyer Instruments Series RHL temperature/humidity transmitter

Parameter	Value/Note
Relative humidity range	0 - 100% RH
Temperature range	-40 to 140°F (-40 to 60°C)
Supply voltage	10 - 35 VDC (loop powered on RH)
Accuracy*	±3% 10-90% RH; ±0.9°F @ 72°F
Supply current	40 mA max
Output type	4 – 20 mA (2 channels)
Enclosure	ABS
RH sensor	Capacitance polymer
Temperature sensor	Solid state band gap
Dimensions	125mm × 80mm × 55mm (enclosure)

TABLE A-3: FEATURES OF THE OMEGA PX-409 BAROMETRIC PRESSURE TRANSDUCER

Parameter	Value/Note
Pressure range	16 – 32 in. Hg
Pressure coupling	¼-18 NPT male
Supply voltage	9 - 30 VDC
Accuracy*	±0.08% BSL
Supply current	20 mA max
Output type	4 – 20 mA
Enclosure	316 SS, IP-76
Electrical termination	2 m (6’) cable termination
**Includes nonlinearity, hysteresis, and non-repeatability*	

TABLE A-4: FEATURES OF THE ALLEN-BRADLEY 1763-L16AWA MICROLOGIX 1100 CONTROLLER

Parameter	Value/Note
Dimensions	90mm × 110mm × 87mm (H×W×D)
Analog input	(2) 0~10V DC
Analog input resolution	10 bit (unsigned)
Analog input non-linearity	±0.5% FS
Analog input overall accuracy	±0.5% FS (-20 to +149°F)
Digital input	(10) 79~132V AC
Digital output	(6) Relay
Communication ports	(1) RS-232/485 combo, (1) Ethernet
Power supply voltage	100~240V AC (-10%,+15%) at 47~63 Hz
User program memory	4k words
User data memory	4k words

TABLE A-5: FEATURES OF THE ALLEN-BRADLEY 1762-IF4 ANALOG INPUT MODULE

Parameter	Value/Note
Dimensions	90mm × 87mm × 40mm (H×D×W)
Number of analog inputs	4 differential (bipolar)
Analog input type	Voltage: -10 to +10V DC Current: 4 to 20mA
Full scale analog ranges	Voltage: -10.5 to +10.5V DC Current: -21 to +21mA
Analog input resolution	15 bit (bipolar)
Repeatability	±0.1%
Typical overall accuracy	±0.3% FS (0 to +55°C) ±0.24% FS (at 25°C)
A/D converter type	Successive approximation
Common mode voltage	±27 V
Common mode rejection	>55 dB at 50 and 60 Hz

TABLE A-6: FEATURES OF THE ALLEN-BRADLEY 1762-OF4 ANALOG OUTPUT MODULE

Parameter	Value/Note
Dimensions	90mm × 87mm × 40mm (H×D×W)
Number of analog outputs	4 single-ended (bipolar)
Analog output type	Voltage: 0 to 10V DC Current: 4 to 20mA
Full scale analog ranges	Voltage: 0 to 10.5V DC Current: 0 to 21mA
Analog output resolution	12 bit (unipolar)
Repeatability	±0.1%
Typical overall accuracy	±1% FS (0 to +55°C) ±0.5% FS (at 25°C)
D/A converter type	R-2R ladder voltage switching
Module update time	2.5 ms

TABLE A-7: FEATURES OF THE ALTECH CORP. PS-1524 POWER SUPPLY

Parameter	Value/Note
Output voltage	24V DC
Rated output current	0.63A
Input voltage	85~264V AC or 120~370V DC
Input frequency	47~63Hz
Input current	0.88A @ 115V AC
Dimensions	25 mm × 93 mm × 56 mm (W×H×D)

TABLE A-8: FEATURES OF THE BALDOR NM3538 VS1MX10P5-2 VARIABLE FREQUENCY DRIVE

Parameter	Value/Note
Power rating	½ HP
Input voltage	99-126V AC 1PH
Output voltage	230V AC 3PH
Output frequency range	0-500 Hz
Enclosure	NEMA 12 / IP55
Input current	6.7 A
Output current	2.3 A
Speed setting	0-10 VDC, 0-20 mA; digital (keypad)
Acceleration/deceleration	0-3000 seconds
Analog output	0-10 VDC, 10mA (1kΩ)
Duty cycle	1.0
Dimensions	164 mm × 200 mm × 166 mm (W×H×D)

B. APPENDIX: PLC DATA ACQUISITION LADDER LOGIC

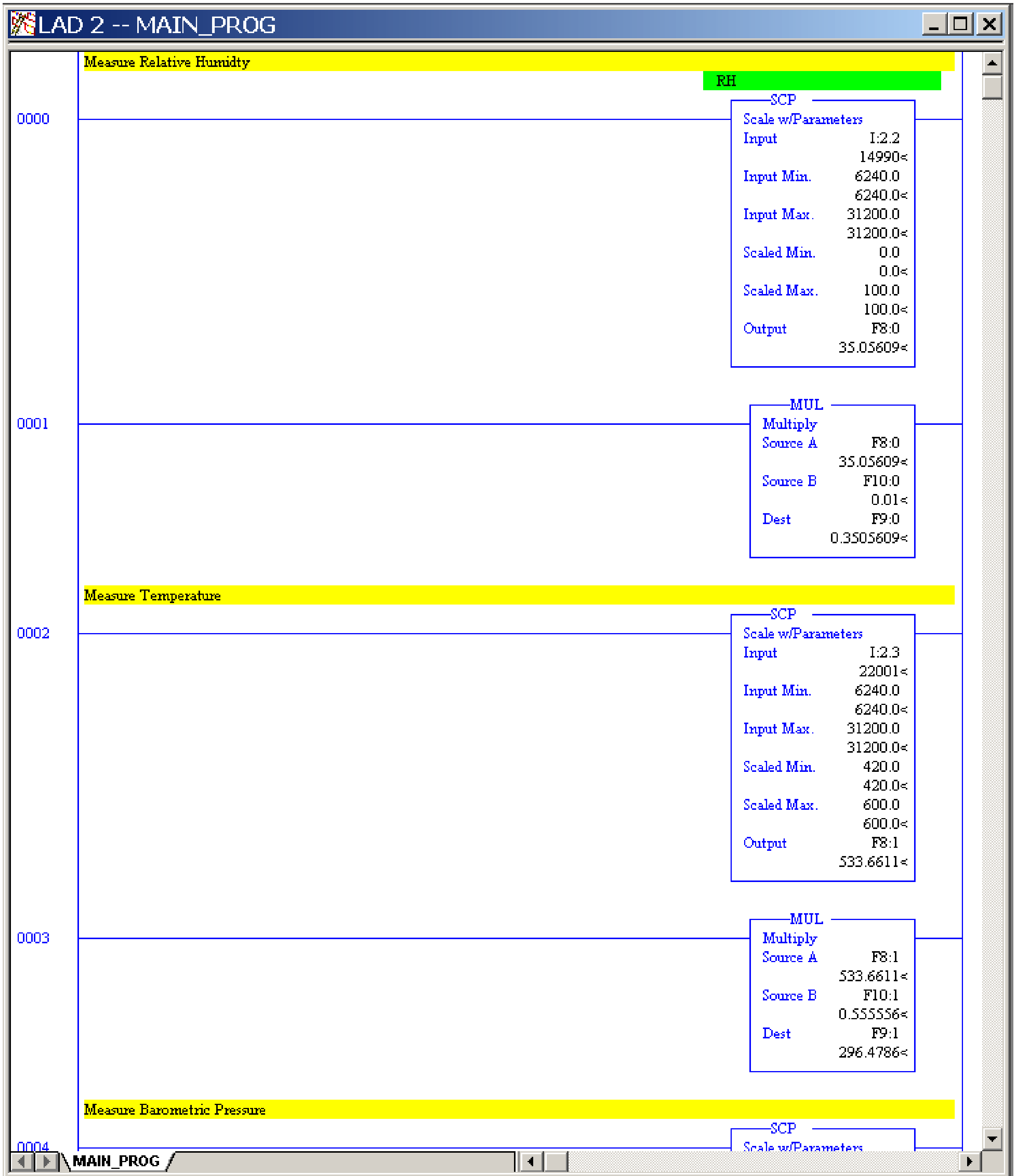

FIGURE B.1. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 1

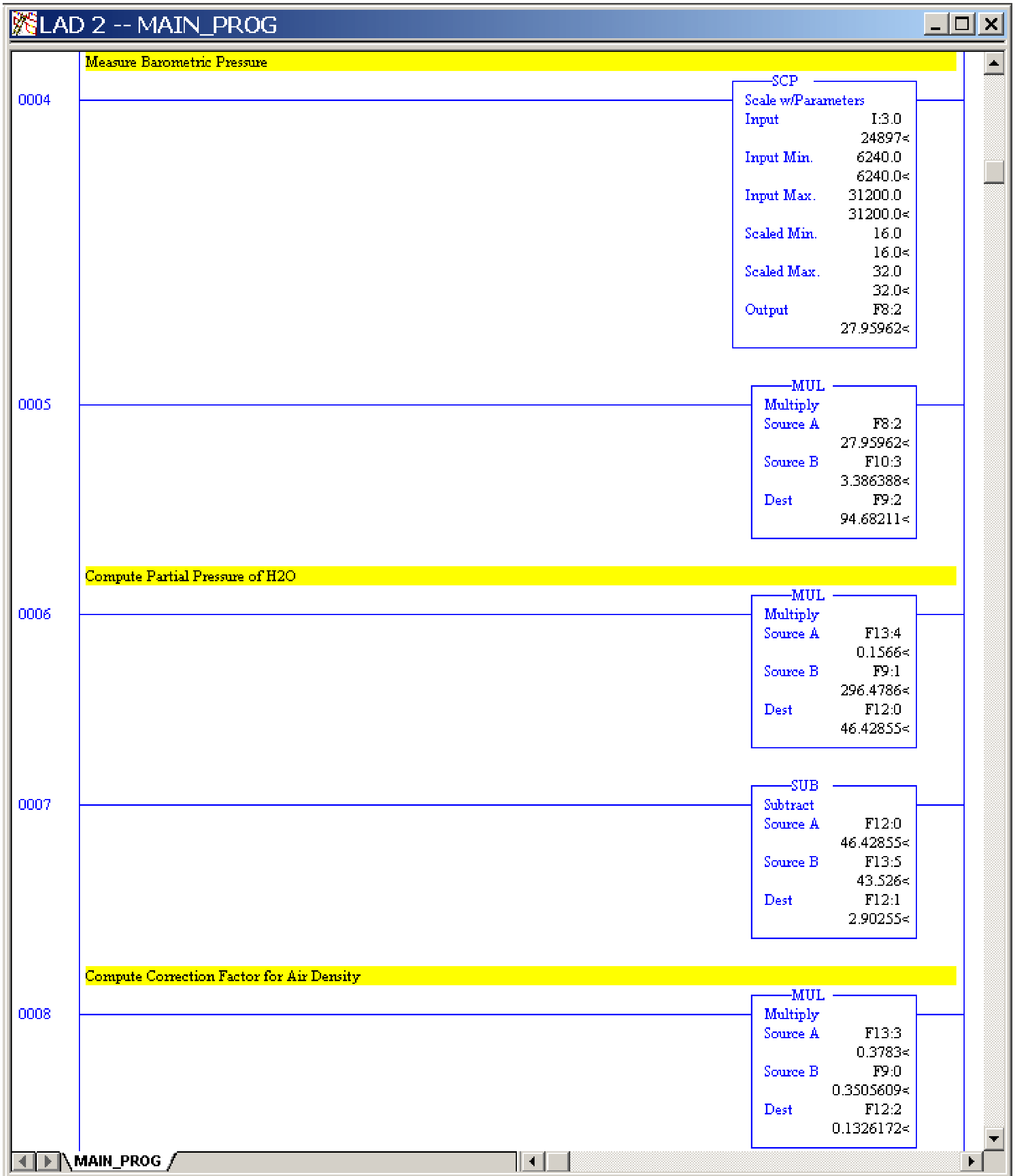

FIGURE B.2. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 2

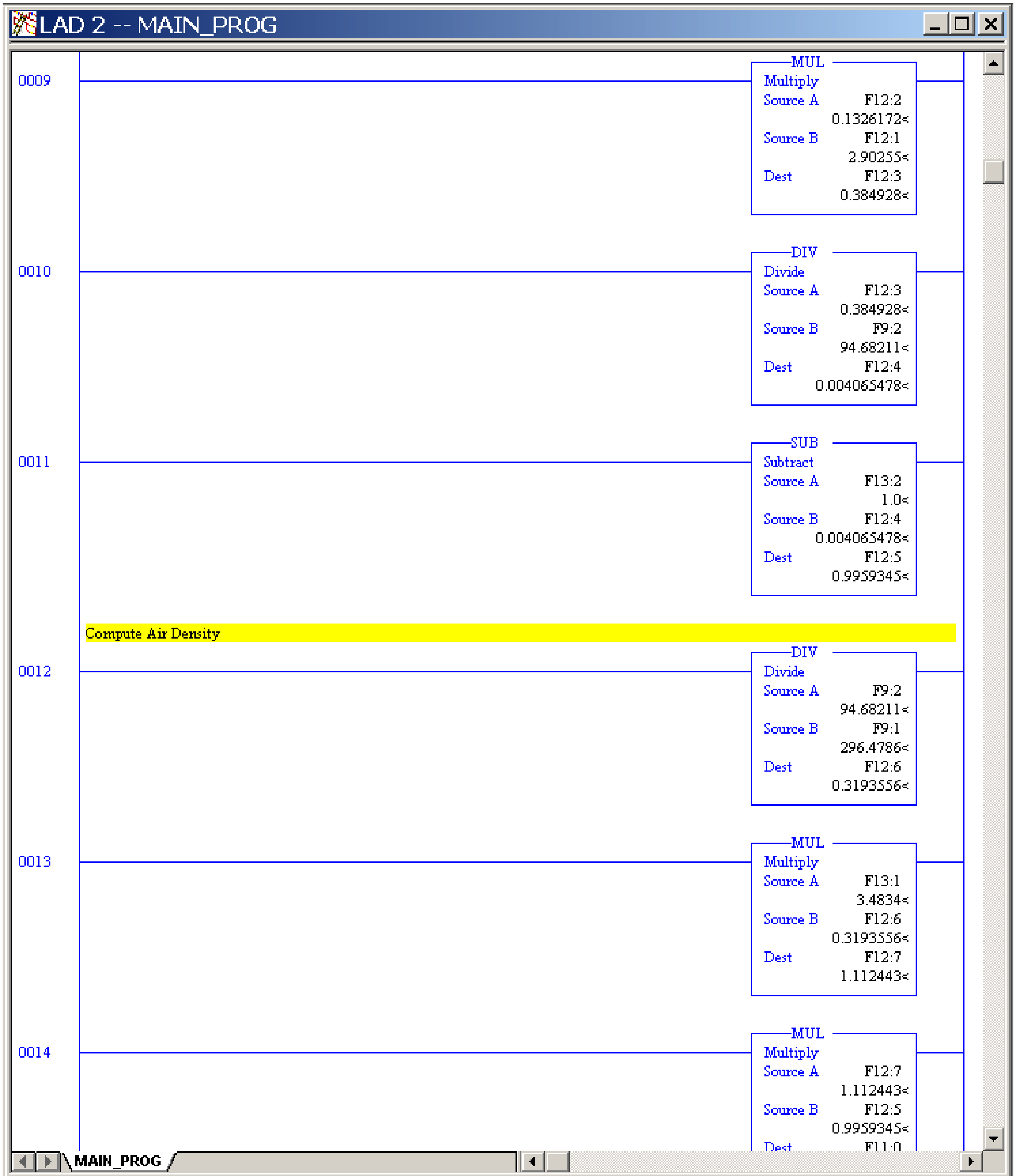

FIGURE B.3. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 3

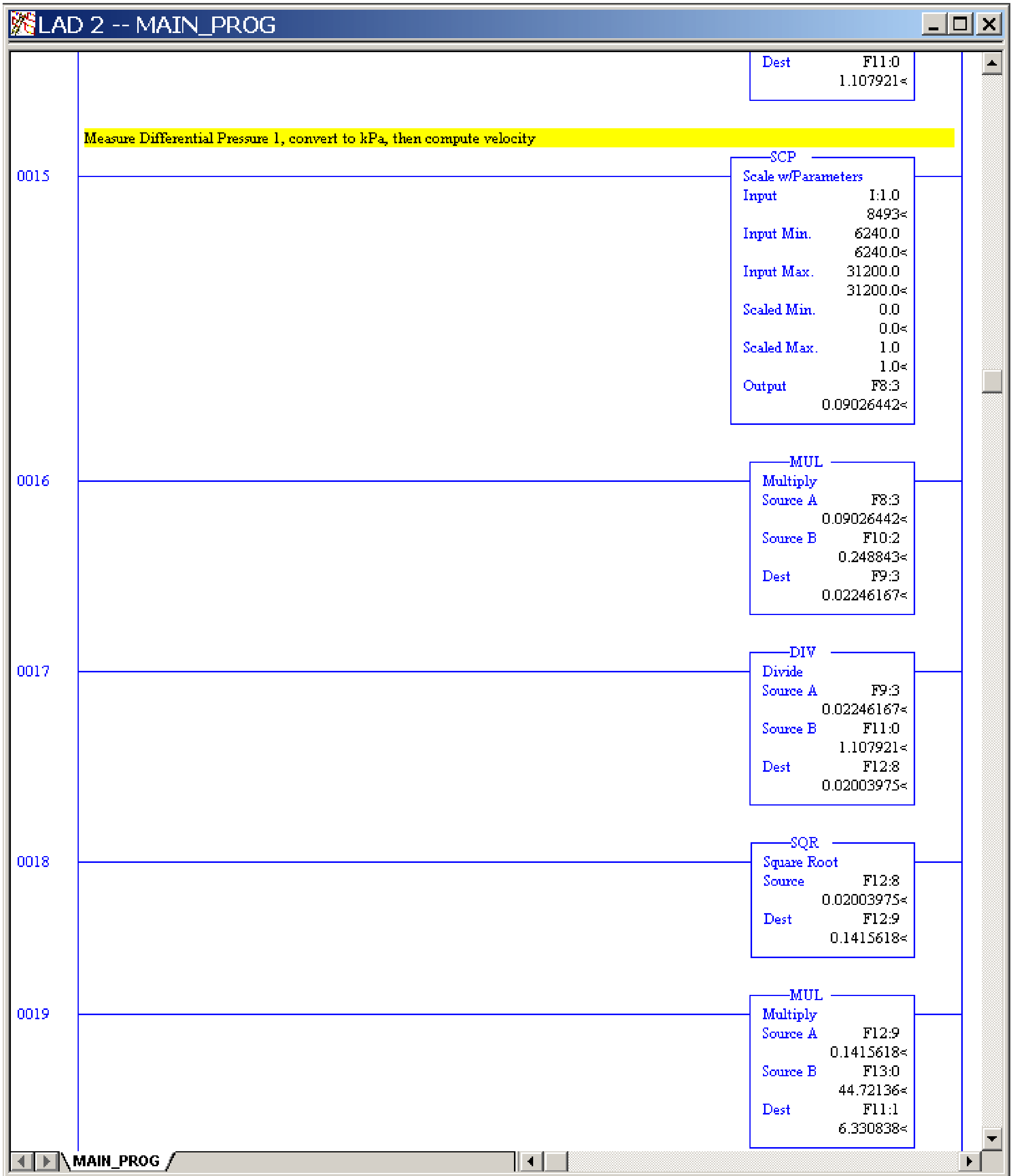

FIGURE B.4. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 4

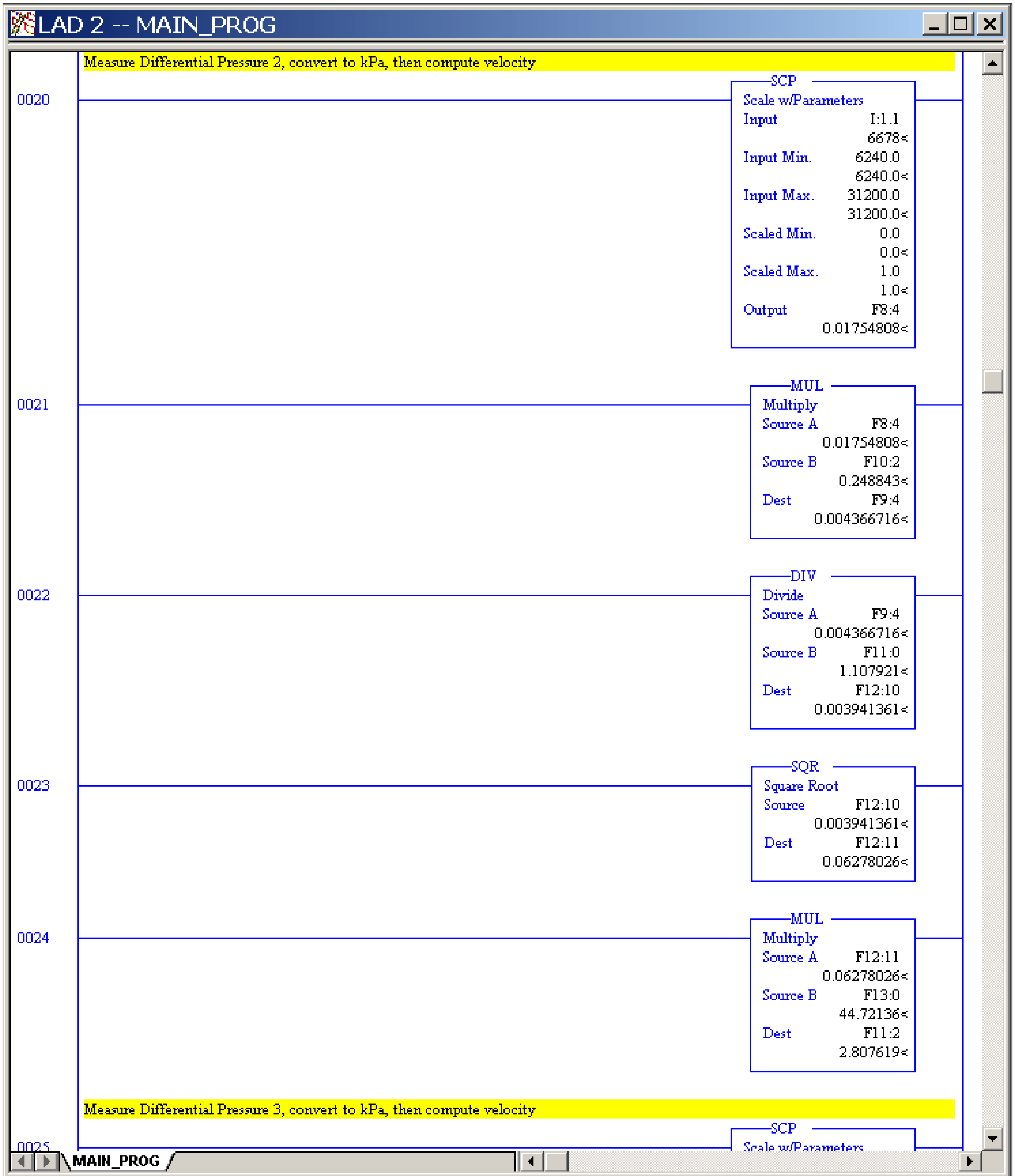

FIGURE B.5. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 5

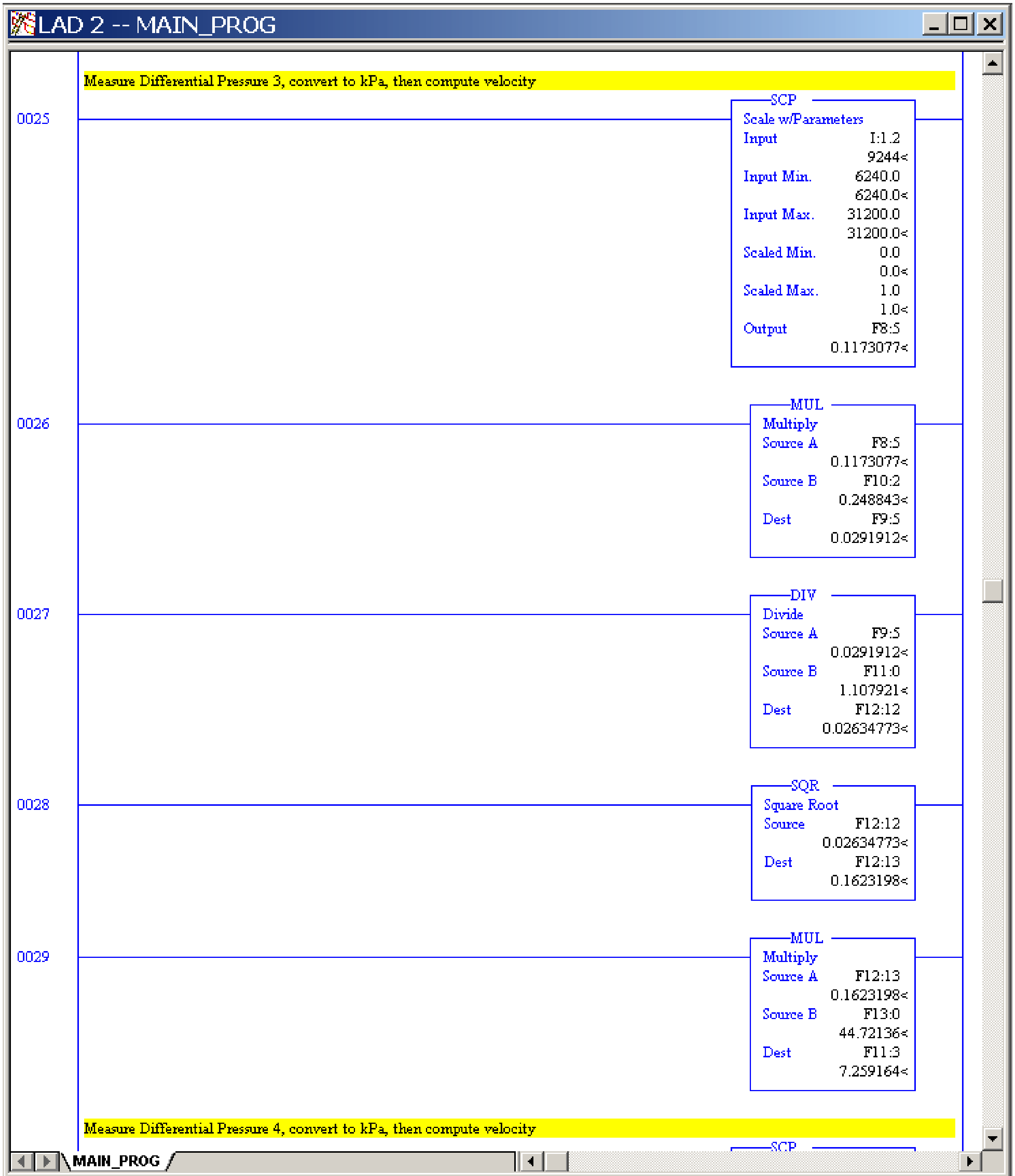

FIGURE B.6. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 6

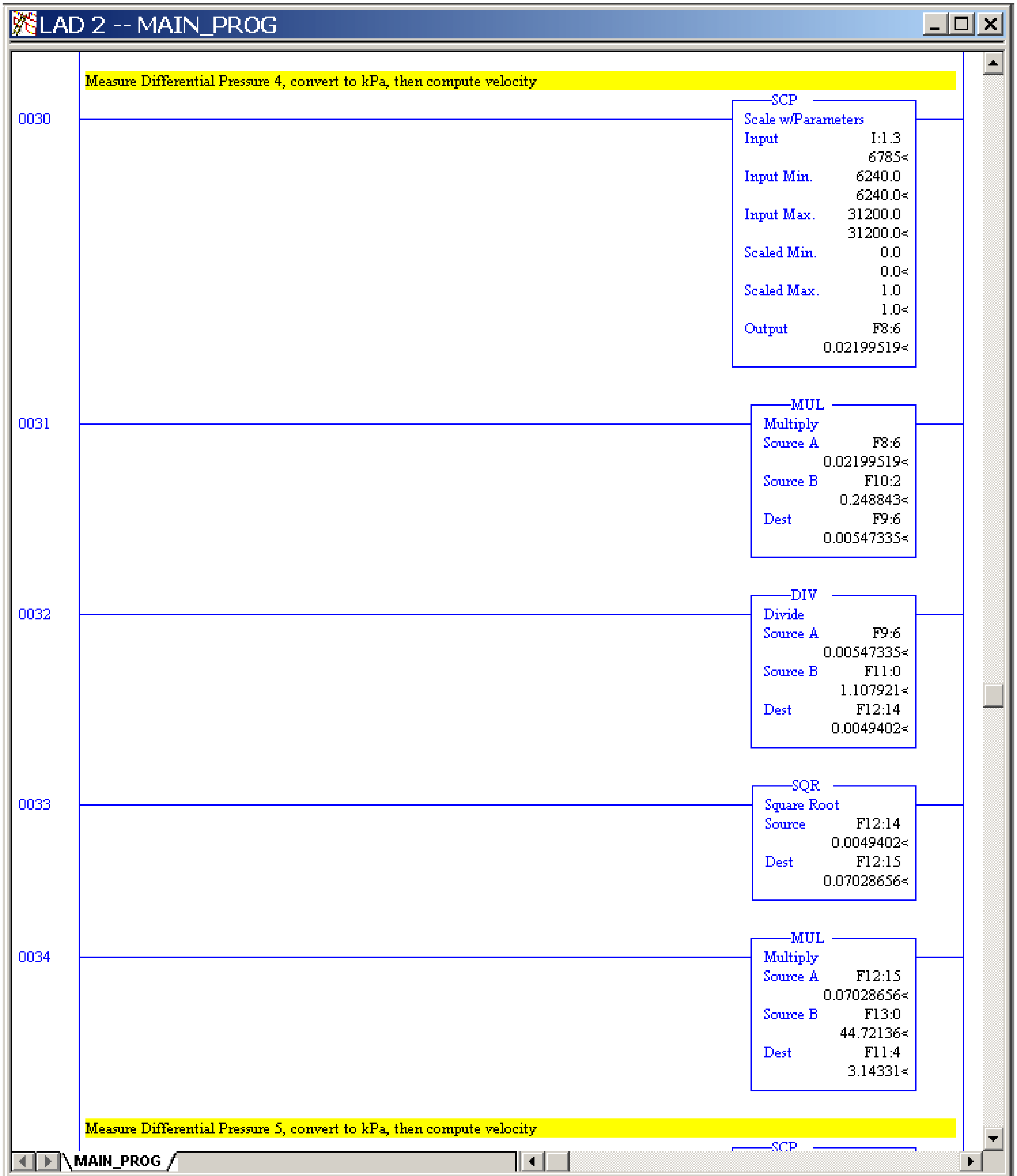

FIGURE B.7. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 7

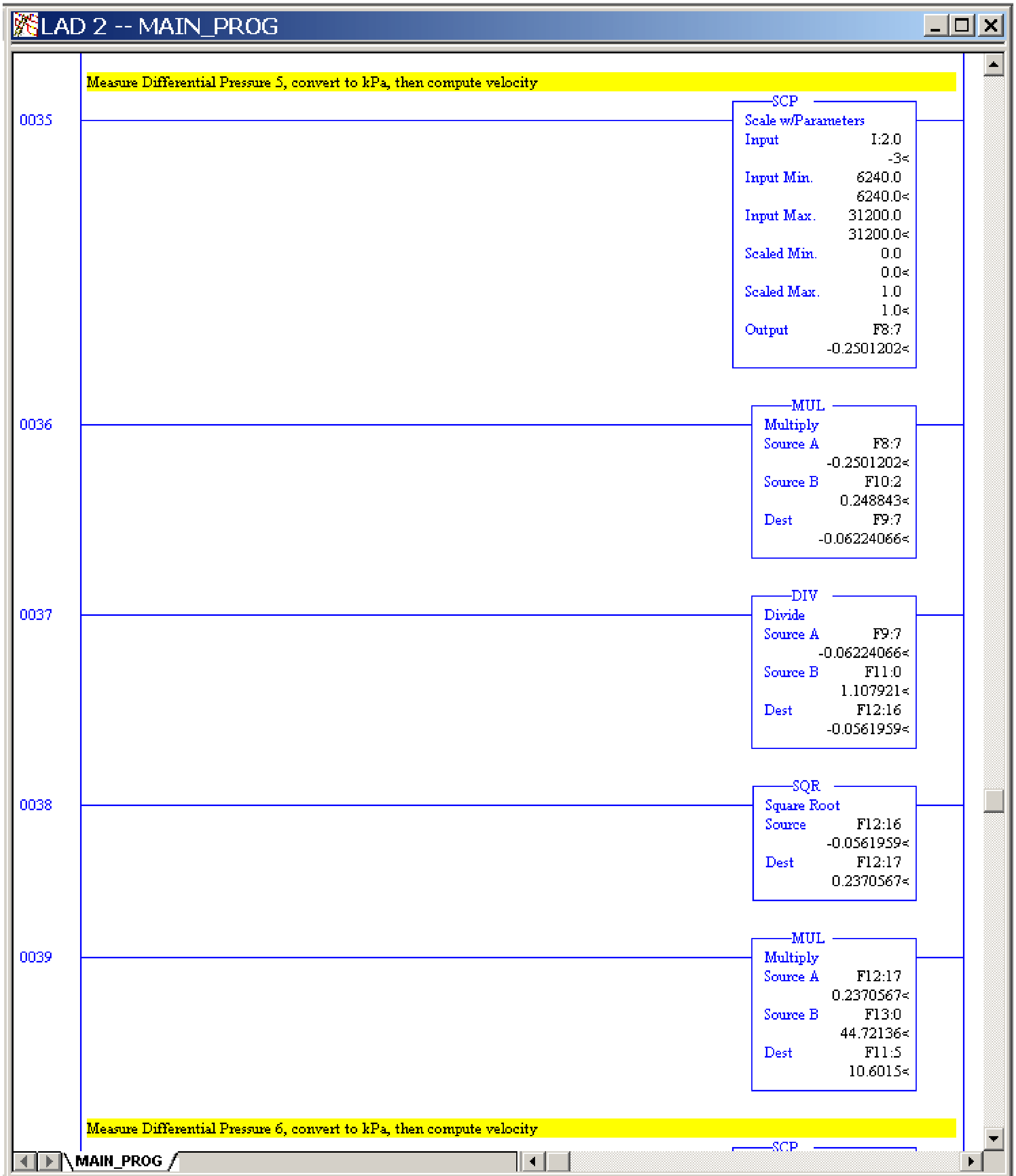

FIGURE B.8. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 8

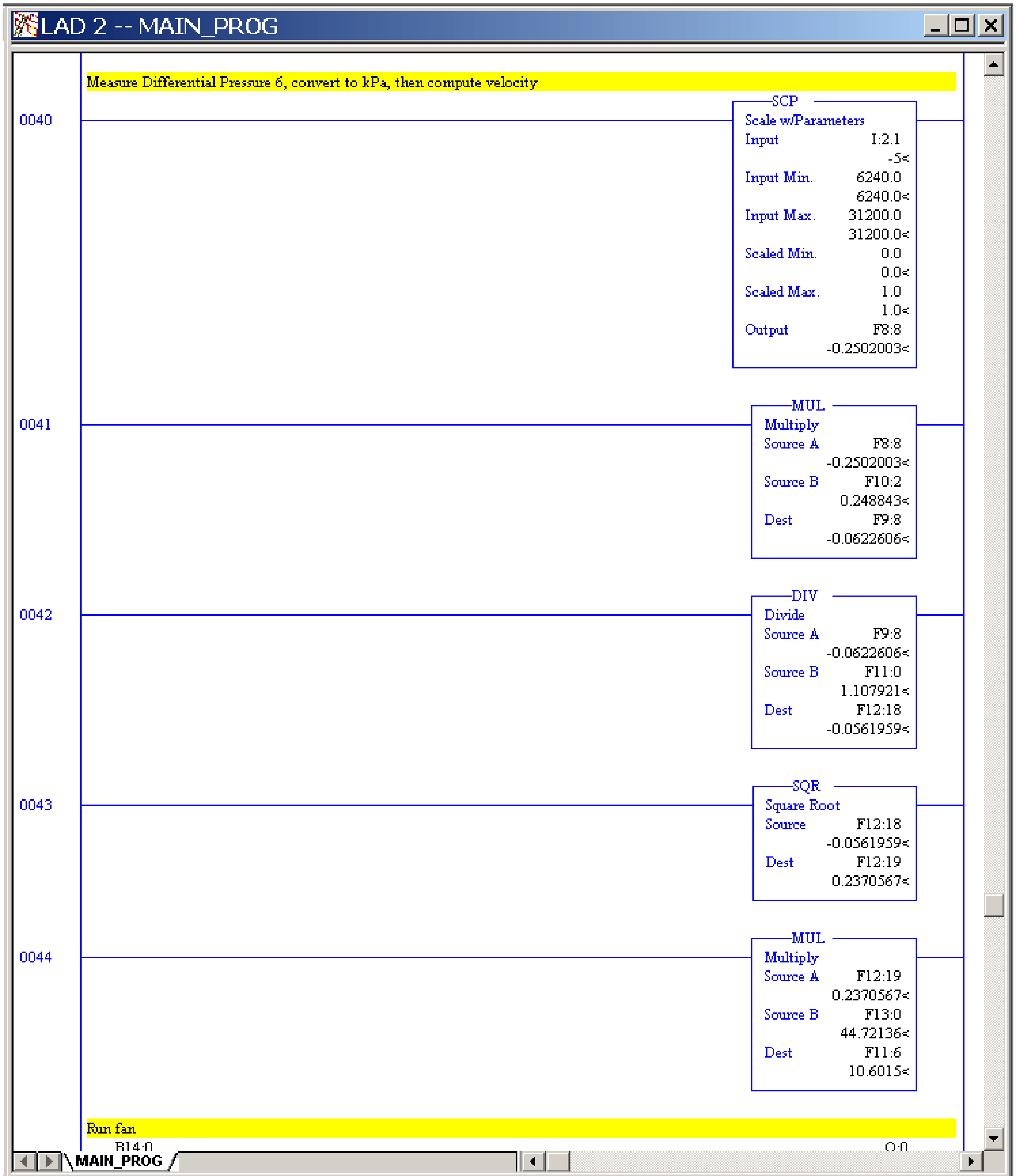

FIGURE B.9. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 9

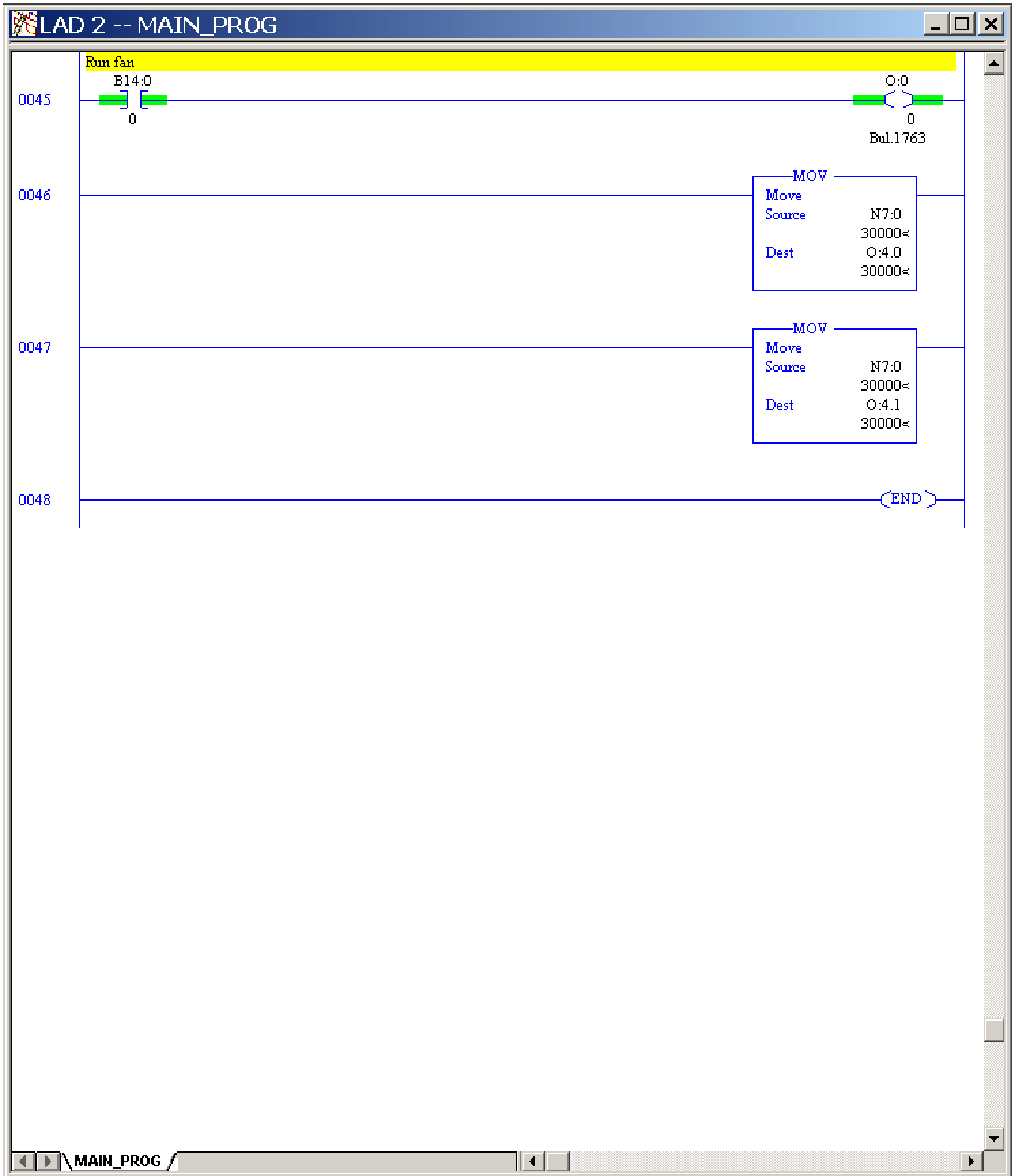

FIGURE B.10. PLC DATA ACQUISITION SYSTEM LADDER LOGIC SCREENSHOT PAGE 10

C. Appendix: Costs of Components

Table C-1: Summary of costs of components

Component	Vendor	Unit Cost	Qty.	Total Cost
PVC pipe and fittings	Ferguson Plumbing	$300	1	$300
Differential pressure transducer	Omega Engineering	$181	6	$1086
Humidity/temperature transmitter	Cole-Parmer	$78	1	$78
Barometric pressure transducer	Omega Engineering	$565	1	$565
MicroLogix 1100 PLC, 3 analog input, 1 analog output modules	Williams Supply	$820	1	$820
Dwyer Instruments Pitot tube	Grainger	$64	6	$384
Radial blower fan	Grainger	$368	1	$368
Baldor NM3538 AC motor	State Electric Supply	$243	1	$243
Baldor VS1-Microdrive VFD	State Electric Supply	$395	1	$395
DIN-rails	Automation Direct	$24	1	$24
Electrical enclosure and parts	State Electric Supply	$366	1	$366
Cable channel	Automation Direct	$18	4	$72
Power supply	Allied Electric	$39	1	$39
22 AWG 2 cond. shielded cable	Lowes	$60	1	$60
DIN-mount circuit breakers	Allied Electric	$11	2	$22
Mini-DIN connectors (20 M, 20 F)	Digi-Key	$45	1	$45
			TOTAL	**$4,867**