## 1.1 Introduction

In today's modern world, convective heat transfer is a process that everybody is exposed to every day. For example, the man on the street uses clothing to control the rate at which heat is transferred from the body to the surrounding environment. For the engineer, heat transfer is an important issue that forms part of almost any engineering design, and the applications range from the cooling of a computer chip to the protection of the Space Shuttle on re-entry into the atmosphere of the earth. The design of that equipment is often based on heat transfer data obtained from experiments. During the experiments, specialized techniques and equipment are used to measure temperature and heat flux.

The wide-spread measurement of convective heat flux became very popular in the 1950's. Since then, numerous different heat flux gages have been developed, and literally hundreds of reviews have been written on the measurement of heat fluxes. Over the past two decades, a few new techniques have been implemented which have led to higher resolutions and wider operating ranges. The largest improvement came with the rapid development in computer technology and in data acquisition systems. Although these techniques revolutionized the measurement of heat fluxes, no single gage or method is the best for each and every application

An important feature of a modern convective heat transfer measuring technique is that it must be non-intrusive. This means that the flow over the surface is not to be obstructed in anyway. Any obstruction in the flow will alter the flux through the surface at that point. It is also important that the gage should not disrupt the heat transfer pattern in the material. If the gage is made of a different material than the material through which the flux is to be measured, the flux through the gage and that through the material under observation will be different. The flux through the gage may be measured accurately, but the actual flux through the adjoining wall will not be the same.

The overall objective of the project, of which this study is a part, is to install a heat flux measuring device into a skin-friction gage of Virginia Tech design. In the past, this gage only measured the skin-friction in a wide variety of flows. A goal of the addition of pressure and heat flux measuring capabilities was set to enhance the overall performance and capabilities of the gage. The first step was thus to include the heat flux measuring capability. Before making a decision like this, it is important to consider all the gages currently available in the literature. A brief review of the literature will be given to discuss the most popular and widely used gages.

## 1.2 Literature

Convective heat flux measurements and gages in general can be divided into a number of categories. Each category has been developed for a specific type of application, and in each category, there are a number of different gages for different situations. The four basic categories can be classified as follows.

- A temperature difference can be measured over a spatial distance with a known thermal resistance.
- A direct measure of the energy input or output can be obtained.
- If the properties of the fluid are known, the flux can be measured by measuring the temperature gradient in the fluid adjacent to the surface.
- A temperature difference can be measured over time with known thermal capacitance.

Irrespective of its application, the following guidelines should be used when choosing a heat flux gage in any one of these categories.

- The size of the gage is very important. The smaller the gage the faster (in general) the time response will be. The location of the gage is known more precisely.
- The gage should not interfere with the fluid flow.
- Most importantly, the thermophysical properties of the material should be the same as or very similar to that of the material of intrest.

A discussion of each of these categories with a brief outline of some of the most common gages in each category will now follow. Spatial temperature difference is the first to be discussed. These gages work basically by measuring the temperature very close to the surface at two points, sometimes very close to each other [1]. This is done by separating the measuring points by a thin material. These gages give output signals proportional to the flux going into and out of the surface.

*Layered gages* are the simpler of these spatial temperature difference gages. The temperature is measured on either side of a thermal resistance layer. See *figure 1.1*. The temperature difference is then proportional to the flux into or out of the surface. These gages vary in size, materials and in the way the temperatures are measured. The sensitivity of these gages is not only a function of the temperatures being measured, but also of the thermal conductivity of the thermal resistance layer and the thickness of this layer. A major drawback of these gages is the fact that they have relatively slow response times, especially if the resistance layer is thick. (1mm will be very thick)

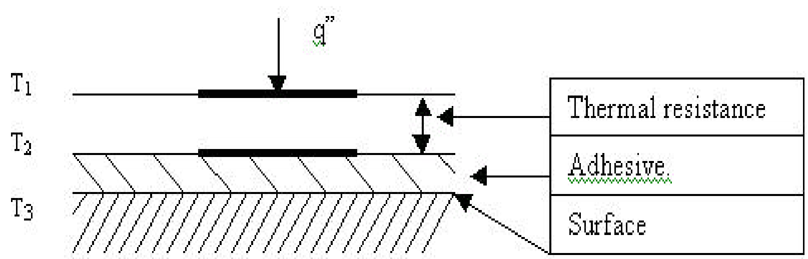


**Figure 1.1 Basic concept of a layered gage.**

A *wire-wound gage* can be used to overcome the problem of time response. Wire wound gages consist of one of the thermocouple wires (say Constantan) wrapped around a thermal resistance layer. One half of the wire is then electroplated with the other thermocouple material for example Copper. See *figure 1.2*. This creates thermocouple junctions on top and at the bottom of the thermal resistance layer. The thermal resistance layer is usually made of a very high thermal conducting material. This is done mainly to minimize thermal disruption in the material. The sensitivity of these gages is good, but one of the drawbacks is the fact that one-dimensional heat transfer is not maintained. This is a very wide spread problem amongst gages. In some gages, this problem is less critical than in others.

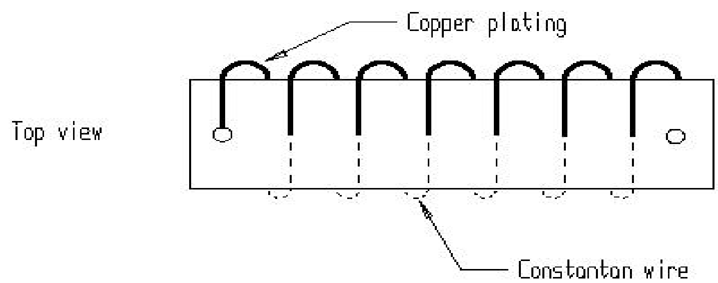


**Figure 1.2 A wire wound gage. Constantan wire on the one side is plated with copper.**

The *in-depth-temperature gages* are the third group in this category. See *figure 1.3*. This technique makes use of the measurement of temperatures at precisely known locations in the wall. These gages are similar to the layered and wire wound gages. The in-depth temperature gage measures the temperature in the wall itself, at two known positions, with a known distance between the two thermocouples. The disadvantage of this technique is that the data reduction is very complex and, in terms of computer time, very expensive. Although boundary conditions might change from installation to installation, it is also difficult to accurately define boundary conditions, when using this type of gage. In the figure below, two Alumel wires were welded to the alloy, in the figure, and the two thermocouples formed in this way can be used to deduce the flux [1].

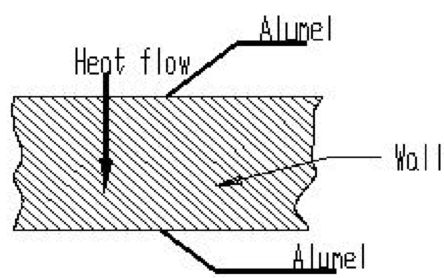


**Figure 1.3 Temperature measurements at two different locations.**

The next category of heat flux gages is called *active heating*. Active heating involves the measurement of the energy flow and then relating that to the flux in and out of the body. This energy is supplied electrically and can be controlled easily and accurately. The energy input to the system can then be related to the flux at the boundary, because the rest of the body is insulated. Heating takes place inside the body and this causes the drawback that the flux is always out of the body. Two important issues are the effect of the thermal capacitance of the wall material, (if steady state is not achieved) and the heat transfer at the end of the measuring region. Very good insulation is important. Small rates of temperature change may cause large errors in the heat transfer measurements. It may also take a while before steady state conditions are reached. In some cases it can take up to 1 hour to reach steady sate [1]. The time constraints in this method make it unsuitable for use in high-heat-flux or high-temperature situations. This rules out most high-speed flows. In our case, the measurement of heat fluxes in hot-high-speed-flows is important, therefore further discussion of these techniques is omitted.

Apart from the active heating techniques there is another category, the *measuring of the temperature gradient in the fluid* next to the wall. This can be done in various ways. Thermocouples probing the fluid at known distances will measure the temperature as a function of time. The flux in the fluid adjacent to the wall can be considered to be the same as that in the wall. This method is also not considered in detail, because it is not used very much in practice and the applications are limited. It is clearly inappropriate in very hot flows. Probing the fluid also includes an obstruction in to the fluid, which might alter the flux.

The fourth and last category in the measurement of heat flux is the *temperature-change-with-time* category. In this approach, the aim is to measure the surface temperature and by means of an inverse mathematical scheme deduce the heat transfer at the surface. The first gage to be discussed in this category is the *slug calorimeter* [1]. This is a device that measures the amount of energy absorbed as a function of time. One temperature measurement at the back represents the entire gage. See *figure 1.4* This assumption can be made only if the thermal resistance of the gage is very low. If we take a control volume around the gage, we can use the conservation-of-energy-principal. The following equation then holds:

$$q = mC\frac{dT}{dt} + q_{losses} \tag{1.1}$$

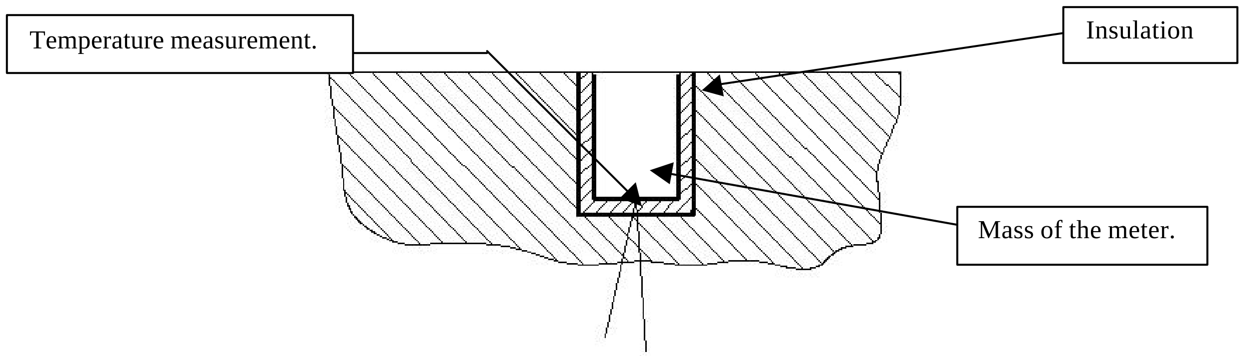


**Figure 1.4 Principle of the slug calorimeter.**

If we assume that the gage is insulated, then the losses can be neglected. As in most gages, the material of the gage should be very similar to that of the wall to minimize temperature profile disruptions. The time response of these gages is, in general, not good. The *null-point calorimeter* (*figure 1.5*) offers an improvement on this drawback [2]. It works basically in the same way as the slug calorimeter. The null-point calorimeter only makes use of a hole drilled in the back to install the thermocouple closer to the surface. By doing this, the transient delay is much shorter, and the response is, therefore, much faster.

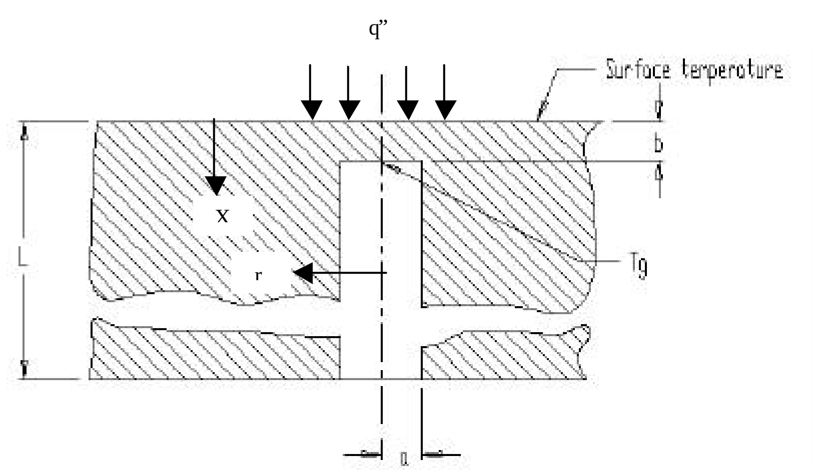


**Figure 1.5 Null-point calorimeter concept sketch.**

In *figure 1.5,* L is the length of the thermal mass, a is the radius of the hole, and b is the distance of the measuring point below the surface. The null-point is the point at x=b and r=0. The transient temperature measured here is assumed to be the same as the surface temperature history.

The *thin-skin method* is a method like the slug calorimeter that covers the entire body of the model. Thermocouples are attached to the backside of the skin to measure the temperature there. The heat flux can be calculated at each location using the same technique as that used by the slug calorimeter. Here, thermocouples with low thermal conductivity should be used. Copper is thus not a good option. The main errors occur as a result of conduction down the thermocouple wires, heat lost through the back surface of the skin and transverse conduction along the skin.

Advances in the fabrication of *thin-film gages* made them largely replace the thin-skin gages [3, 4]. These gages can be made very thin (~ 1μm) This improves the response times of these gages greatly. They make use of hundreds of thermocouples arranged in a differential thermopile that gives a voltage output proportional to the heat flux. One of the biggest drawbacks when using these gages for high-temperature flows is that the gages are exposed to the hot high-speed flows, and they may encounter damage during the test runs. These gages measure the surface temperature in response to the surface heat flux. The data analysis is the same as that used for null-point calorimeters and coaxial thermocouples (Discussed in the next paragraph.) The largest difference between the *thin-film* gages and the coaxial thermocouple and the calorimeter is that the *thin-film* gage is mounted on the surface of a homogeneous solid [1]. The other two gages measure the temperature on a non-homogeneous plug inserted into the solid.

The last gage in this category is the *coaxial thermocouple* type gage. See *figure 1.6*. In the case of a coaxial thermocouple, the idea is to measure the surface temperature as a function of time. Coaxial thermocouples are much easier to fabricate than their calorimeter counterparts. These thermocouples can be made very small, which increases their sensitivity as well as their response time. The sensitivity and response time are increased due to the smaller thermal mass that needs to be heated to a specific temperature. A very important issue when using these types of thermocouples to “measure” heat transfer is to match the physical properties of the surrounding wall very closely. The product, $k\rho C_p$, of the thermocouple and that of the wall, should be similar.[2] This is possible when one considers the fact that thermocouples can be made of virtually any two metals. By using one metal of the same thermophysical properties as that of the wall and the other a very thin wire, the thermocouple as a system can be made to have physical properties close to that of the wall.

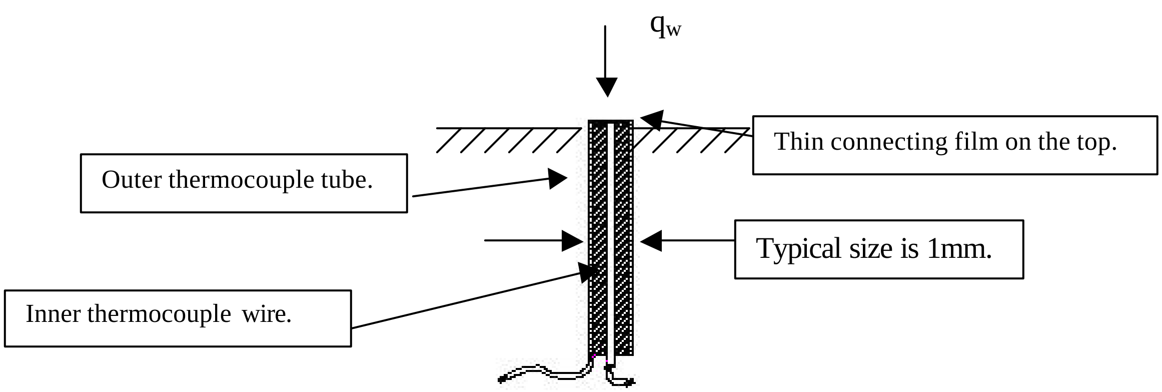


**Figure 1.6 Coaxial thermocouple.**

In the present study, the surface temperature change with time type of method was chosen. The coaxial thermocouple for measurement of the surface temperature, was chosen for the following reasons:

- Coaxial thermocouples can be made very small (on the order of 0.005")
- They can be installed flush with the surface and, therefore, not interfere with the flow of fluid over the surface.
- Thermocouples can be made of materials with physical properties very close to the material through which the flux is to be measured.
- Robustness of the thermocouples is also important to note. Care should be taken when handling them, but once installed they can have a relatively long service life.
- Despite their cost relative to other thermocouples, they are much less expensive than heat flux sensors. A heat flux sensor is essentially what is needed.

Difficulties arise when the temperature being measured in this way is to be transformed to the flux through the surface. When using a thermocouple to evaluate the temperature on the surface and relating this to the flux through the wall a numerical procedure should be incorporated to convert the temperature to heat flux. This procedure of reducing the temperature data to heat flux will be discussed in the following section – *Data Reduction*.

## 1.3 Data reduction

In the current work the reduction of data is a very delicate process. High heat fluxes like those used in the very harsh environments of ramjet and scramjet engines, as well as those introduced by shocks during high-speed flows are generally obtained by measuring the temperature on the surface. By using this data together with some data reduction scheme, the surface temperature time history can be converted to the correct flux into the body under consideration. This way of evaluating the flux is, however, not free of its problems. Mathematical instabilities are inherent in the solutions.

If one examines the relationship between the measured surface temperature and the heat flux this will become clearer [5]. The conventional temperature solution for conduction through a body can be expressed as some integral of the flux at the boundary.

$$\mathbf{T(x,t)} = \int_0^t q(t)G(x,t)\ \mathbf{dt} \tag{1.2}$$

Where q(t) is the boundary flux we are searching for, and G(t) is some characteristic function such as Green's function [6,7]. In this case x = 0. (Surface.) This is a Volterra equation whose solution is known to be difficult to find. This is actually very simple to understand if one remembers that an integral is just the area under a curve. Obviously, different curves can have the same area beneath them. The solution to the problem is thus not unique. The fact that the solution is not unique complicates the solution tremendously. To get **q(t)G(x,t)** one has to differentiate the temperature**.** The differentiation process causes instabilities in the problem solution. Differentiation of data is inherently unstable, because small errors are amplified a great deal when running data through a differentiation scheme.

There are basically three different classes of methods to do the reduction of the data. A full explanation will follow later in this chapter. The first class uses an analytical approach to the problem and may be called *Forward Analytical*. The second class, approach the problem in a numerical way, thus it is named as *Forward Numerical*.

The third and last class makes use of an *inverse* technique. The inverse technique works by estimating a solution that is already known, from a guessed input. In this case, the solution will be the temperature. In calculating this known value, the program will have to guess a certain input, here this is what is sought, the heat flux at the surface. The output, which is calculated, is then compared to the measured value. The input is altered to make the output of the program and the measurements coincide. Using this inverse approach eliminates some of the unwanted instabilities in the data reduction through the introduction of bias [6]. This thesis is based on the inverse approach and specifically the extension of a code written by Greg Walker on this inverse approach [5]. One of the main differences of the modified code used in this thesis is that the code is no longer restricted to the semi-infinite solid approach of the original code. Two temperatures are now measured at the surface and back face of a slab, and the inverse scheme then alters the temperature profile through the body until the guessed surface heat flux reveals temperatures that are equal to the measured ones. The surface heat flux is then estimated at this specific point in time.

The three different methods for calculating heat flux from temperature measurements will now be discussed. They are: Forward Analytical: Class 1, Forward Numerical: Class 2 and Inverse: Class 3 methods. Because surface temperature measurements are made, the data taken can be used as a boundary condition for the forward conduction problem. The flux on the surface can then be found as a function of the surface temperature measurements.

## Forward Analytical: Class 1

The flux at the surface can only be obtained through relation of the surface temperature to an arbitrary flux by means of the conduction equation. The temperature solution will then be a function of the flux to be determined and of time and space. The solution can only be found if the temperature on the surface is assumed to be piecewise linear and that the properties of the object are not temperature dependent. This is one of the drawbacks of these techniques. When looking at the stability and accuracy of these methods, the outcome is not very good. For a detailed evaluation of these methods and their characteristics, refer to Walker [5].

The Cook-Felderman method was one of the Class 1 methods evaluated in the current work. This first approach was studied to get an understanding of these numerical methods used to calculate the flux through the boundary. Cook and Felderman in the late 1960's developed an analytical method for the determination of the flux at the surface of a semi-infinite medium [3, 9, 10].

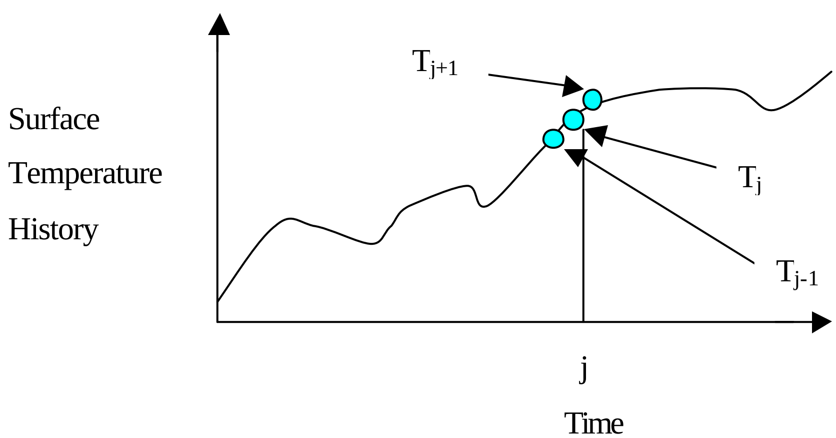


**Figure 1.7 Illustration of the Cook-Felderman technique.**

The Cook-Felderman technique uses the surface temperature as a function of time to calculate the flux. Surface temperature values at different times (in this case j and j-1) are used for the calculation. See *figure 1.7.* Their approach was based on the voltage change E(τ) of a thin film on the surface of a substrate. This voltage change is, directly and linearly proportional to the temperature change on the surface. According to them, the following relation holds for the surface flux:

$$q(t) = \frac{b}{p^{\frac{1}{2}} a E_f}\left[\frac{E(t)}{t^{\frac{1}{2}}} + \frac{1}{2}\int_0^t \frac{E(t) - E(t)}{(t-t)^{\frac{3}{2}}}\,dt\right] \qquad (1.3)$$

In this equation, β, α and $E_f$ must be determined. β comes from Skinner's method - $\beta=(k\rho C_p)^{1/2}$ , α can be determined from static measurements of film resistance vs. temperature, and the initial voltage drop $E_f$ can easily be measured. In general, the quantity within the brackets in Eq. (1.3) should be evaluated numerically. Numerical integration of Eq. (1.3) is necessary because E(τ) can not be described in many cases with a simple expression. For a constant heat flux Eq. (1.3) can be evaluated analytically:

$$q(t) = \frac{1}{2} p^{\frac{1}{2}} b \left[ \frac{1}{aE_f} \right] \left[ \frac{E(t)}{t^{\frac{1}{2}}} \right] \tag{1.4}$$

Therefore, if the response of the thin film (or the surface temperature) is parabolic from τ=0, (in other words T ~ $\sqrt{t}$ ) the heat flux is constant, and Eq. (1.4) can be applied directly to obtain q(t). In most cases, however, the flux is not constant, and Eq. (1.3) must be used.

One can attempt to evaluate the integrand with traditional methods like Simpson's rule or the trapezoidal rule. With either of these methods, the difficulty arises when one attempts to evaluate the integrand at the upper limit, t. In this case, the integrand becomes 0/0, and by application of L'Hospital's rule, the result is infinite at τ = t. Cook and Felderman overcame this problem by approximating E(τ) by a piecewise linear function of the form:

$$E(t) = E(t_{i-1}) + \frac{E(t_i) - E(t_{i-1})}{\Delta t}\left(t - t_{i-1}\right) \tag{1.5}$$

where:

$t_{i-1} \leq \tau \leq t_i$ $\quad$ i = 1, 2, 3, ...,n

$\tau = t_i = i\Delta t$ $\quad$ i = 1, 2, 3, ...,n

$\Delta t = t/n$

If this equation is substituted into Eq. (1.3), the following expression is obtained:

$$q_n(t) = \frac{b}{p^{\frac{1}{2}} a E_f}\left[\frac{E(t_n)}{t_n^{\frac{1}{2}}} + \sum_{i=1}^{n-1}\left\{\frac{E(t_n)-E(t_i)}{(t_n - t_i)^{\frac{1}{2}}} - \frac{E(t_n)-E(t_{i-1})}{(t_n - t_{i-1})^{\frac{1}{2}}} + 2\frac{E(t_i)-E(t_{i-1})}{(t_n - t_i)^{\frac{1}{2}} + (t_n - t_{i-1})^{\frac{1}{2}}}\right\} + \frac{E(t_n)-E(t_{n-1})}{(\Delta t)^{\frac{1}{2}}}\right] \tag{1.6}$$

This equation involves no integration approximations. The accuracy of the result is limited to the degree to which the true function E(τ) is approximated by the piecewise linear expression of Eq. (1.5) A simplified version of this equation can be found in an article written a few years later, in 1970, by Cook [9]:

$$q(t_n) = \frac{2\sqrt{krC_p}}{\sqrt{p}}\sum_{j=1}^{n}\frac{T_j - T_{j-1}}{\sqrt{t_n - t_j} + \sqrt{t_n - t_{j-1}}} \tag{1.7}$$

Where:

| | |
|---|---|
| q | = Heat flux (W/m$^2$); |
| k | = Thermal conductivity (W/mK); |
| ρ | = Density (kg/m$^2$); |
| $C_p$ | = Specific heat capacity (J/kgK); |
| $T_j$ | = Temperature at time j; |
| $t_j$ | = Time at the end of the j$^{th}$ time intervals. |

Diller and Kidd [2] did a modification to the Cook-Felderman [3] technique. They proposed the following equation for the calculation of the heat flux:

$$q(t_n) = \frac{\sqrt{krC_p}}{\sqrt{p\Delta t}}\sum_{j=1}^{n}\left[\frac{T_j - T_{j-1}}{\sqrt{n+1-j}} + (T_{n+1} - T_n) + \frac{1}{3}(T_n - T_{n-1})\right] \tag{1.8}$$

According to the authors, the first additional term adds the next term's influence, which accelerates changes in a more stable fashion than derivative terms. The next term amplifies the influence of the current temperature. The second term, however, decreases the stability and should be kept as small as possible. This new method is as simple as the Cook-Felderman technique, but the effects of noise are reduced by a small amount. For any further information on the development of this method refer to the bibliography. Note that throughout this thesis this method will be referred to as the *Diller Method.* A more detailed evaluation of the Cook-Felderman method will follow in Chapter 2.

## Forward Numerical: Class 2

Class 2 techniques include fully numerical approaches. This was done to eliminate the primary drawbacks of the Class 1 problems, which include the restriction to constant properties. When using Class 2 methods, numerical techniques must be used to evaluate the temperature distribution instead of using analytical methods. The basic difference between Forward Analytical: Class 1 and Forward Numerical: Class 2 methods is that the one uses an analytical approach and the other a numerical one. The first class uses the flux as the boundary condition, and the second class uses the temperature as the boundary condition. In Class 2 methods, the heat flux is obtained by using the derivative of the temperature profile at the surface. Two Class 2 methods will be discussed briefly - the explicit finite difference method and the implicit finite difference method.

The explicit finite difference method is similar to the Class 1 methods, but now the measured temperature on the surface is the boundary condition, and the temperatures at the other nodes in the grid are calculated by solving linearized equations with an iterative scheme. The physical properties of the materials are allowed to change with temperature in this case. It is precisely this fact that will cause the solution equations to be non-linear. This makes the solution difficult and unstable [5, 11].

The governing equation for the 1-D unsteady case is.

$$\frac{\partial}{\partial x}\left[k(T)\frac{\partial T}{\partial x}\right] = \frac{1}{r c_p(T)}\frac{\partial T}{\partial t} \tag{1.9}$$

with boundary conditions

$T(t=0)=T_o$

$T(x=0,t=t_n)=Y_n$ ($Y_n$ is the measured surface temperature at time step n )

$T(x \longrightarrow \infty) = T_0$

With these equations, the temperature distribution in the material can be found, and following that the flux is resolved by means of an energy balance. Although this technique can model temperature dependent properties, its major drawback is the fact that it suffers from grid spacing problems. The gradients of the temperature profiles can be so large, that grid spacing must be very small in order to capture the true flux at the surface. See *figure 1.8*. This is fairly difficult, because the solution converges slowly with decreasing grid spacing.

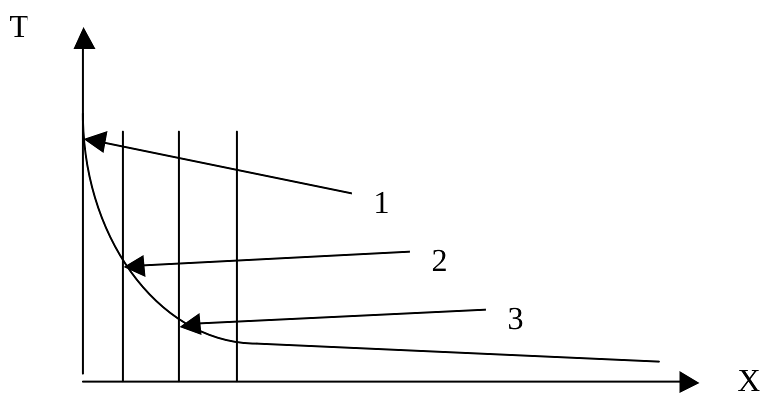


**Figure 1.8 Illustration of grid spacing problems that might occur.**

If the y-axis is on the surface and the curved line represents the temperature distribution in the solid, then point 1 will be the node on the surface and node 2 will be the first temperature node in the solid. To calculate the flux, the gradient between the surface and the first node is needed. If the grid spacing is doubled, i.e. point 3 is the first node in the solid, then the flux estimate will not be close to the first estimate. Therefore, the smaller the grid, the more accurate the flux will be. This is however not a criteria in the case of the inverse schemes, because the flux is no longer obtained from the slope of the temperature profile at the surface. It is also important to note that the explicit method is only stable for Fourier number values smaller than ½. As a result of these problems with the grid spacing and the limitation on the Fourier number in the explicit finite-difference method, the focus moved to the implicit method. The equations are:

$$a(T)\frac{\partial^2 T}{\partial x^2} = \frac{\partial T}{\partial t} \tag{1.10}$$

$$T(t = 0) = 0$$

$$\left.\frac{\partial T}{\partial x}\right|_{x \xrightarrow{} \infty} = 0$$

Although *equation 1.10* imply that the properties of the material are temperature dependent, that is not the case in the current study. Writing the conduction equation in the Kirchoff form and discretisizing implicitly, gives the formulation:

$$\frac{T_i^{j+1} - T_i^{j}}{t_{j+1} - t_j} = a\,\frac{T_{i+1}^{j+1} - 2T_i^{j+1} + T_{i-1}^{j+1}}{\Delta x^2} \tag{1.11}$$

The right hand side of this equation is evaluated at time step j+1. In the explicit form the equation would have been evaluated at time j. Although it is more difficult to solve a system of coupled equations than uncoupled, like in the explicit case, the implicit method has no restriction imposed on the size of the Fourier number, and for that matter the time step $\Delta t$ and has the advantage for situations where larger $\Delta t$ may be needed in order to proceed with to solution more rapidly [12]. This makes the implicit approach inherently stable, therefore the use of this method is preferred over explicit methods. Measurement errors in these methods still cause a high sensitivity in the surface derivative. The derivative of the temperature profile is still used in the determination of the surface flux.

## Inverse method: Class 3

Data reduction in the past was divided into two groups based on the approach followed. The analytical approach of class one methods suffers from constraints such as constant properties. Thus, complex conduction models can not be solved. Class 2 methods on the other hand can treat the complexity not manageable by Class 1 methods, but they suffer from grid sizing problems and discretized data. Thus, new approaches have been sought.

The inverse heat conduction problems are Class 3 methods. There are basically three sub-classes of inverse problems. First there is the backwards or retrospective problems. Then there is the coefficient inverse problem. In these problems a parameter in some governing equation is to be found. Thirdly there are the boundary inverse problems. This is the relevant one in this thesis. In these problems one is looking for the flux at the boundary, for example. A flux is then guessed for each point in time. This guessed flux is then used to calculate the surface temperature(s). This calculated temperature is then compared to the actual measured temperature(s) on the surface. The flux is then corrected until the measured and the calculated temperatures match to some predetermined error margin. The great Russian proponent Prof Alifanov's definition of inverse problems was: "The solution of an inverse problem entails determining unknown *causes* based on observation of their *effects*." (http://www.me.ua.edu/inverse/whatis.htr )

Compared to Class 1 and 2 methods is the fact that in contrast to Class 1 methods, variable physical properties can now be included. Compared to the Class 2 methods discrete data is no longer differentiated. More detail on the inverse technique will be given in Chapter 3.

## 1.4 Application and motivation for this study

In this particular application, the development of a heat flux sensor that will be capable of measuring the flux in very harsh environments was pursued. The future goal was to incorporate this sensor into an existing skin-friction measuring device.

The effective measurement of heat flux will improve the knowledge of flow in ramjet and scramjet combustion chambers and other similar hostile environments. Heat transfer measurements are of extreme importance in these harsh environments because temperatures can range from 2000 $^{o}$C and upwards while the static pressure is in the range of 1 atm. These extreme environments require the latest high-tech materials to be used in the manufacturing of these measuring devices. Another important objective is to make these sensors as small as practically possible to be able to measure heat flux in very small confined spaces and to minimize the weight of these devices. Today, many different heat flux gages are available on the market, but these are usually too large to be installed in a small multiple sensor gage such as the "skin-friction – heat transfer" gage under consideration here. It is also important to keep the thermo-physical properties of the gages close to that of the material through which the flux is to be established and a prebuilt gage can not be customized to the particular application. As opposed to some of the gages mentioned in section 1.2 the coaxial thermocouple and the thermocouple at the back is much simpler to design and manufacture than layered gages, for example [10]. Another advantage of using the coaxial thermocouple is that the "footprint" of the gage can be made very small.

An inverse method is adopted here for its simplicity, stability (low noise) and accuracy. Using the inverse method proves to be very stable and the noise amplification on the flux signal due to the noise on the temperature signal is much less than other forward methods, like Class 1 and Class 2 methods. The accuracy of this method also proves satisfactory when compared to some analytically calculated answers.

## 1.5 Objective

One of the aims of this study was to reconsider the traditional methods of heat flux conversion from temperature measurements. This was done, by evaluating a very well known technique in the heat flux measurement world, the Cook-Felderman technique. Secondly, the inverse approach was selected to estimate heat fluxes by measurement of the surface temperatures. Here, the aim was to critically evaluate a computer code developed previously at Virginia Tech by Walker. [5] The third and last goal was to modify the code to incorporate different boundary conditions. The basic layout of the following chapters are briefly discussed below:

- The Cook-Felderman technique will be discussed in detail. Experimental results, using the data reduction scheme of Cook and Felderman, will be also be shown in Chapter 2.
- Chapter 3 will consist of a brief outline of the basic concept used by Walker.

- In the fourth Chapter, the modification made to the original code of Walker will be discussed. The experimental setup used for validating the accuracy of the code against the experiments, will also be discussed as well as the data acquisition systems.
- In Chapter 5, one of the major concerns, which was 2-D heat flow effects, are discussed.
- Chapter 6 will consist of consideration of the errors in the new approach and the evaluation thereof.
- The last chapter, Chapter 7 will conclude the report. This will include a summary of the thesis in general, the main contributions of the study to the engineering world and areas of further research.