6.1 Comparison of results

An evaluation of the extended code can first be done by comparing the values obtained with the HFS heat flux gage and the flux numerically deduced from the surface temperature history measured by the Medtherm thermocouple. Although the two temperatures measured by the Medtherm thermocouple and the RTS temperature from the heat flux gage are very similar, the RTS temperature seems to lag that of the Medtherm thermocouple. See *figure 4.11*. This could be due to the fact that the thermal mass of the HFS heat flux gage is more than that of the Medtherm thermocouple. Secondly, the thermophysical properties of the heat flux gage do not match up with that of the blade as closely as the coaxial, aluminum thermocouple does.

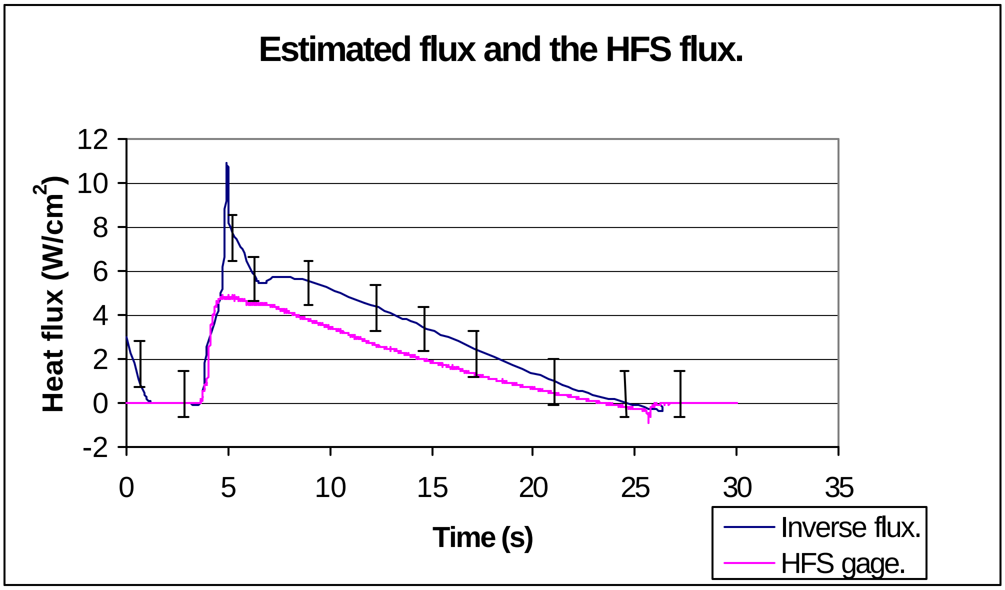

Figure 6.1 Comparison of the two heat fluxes from the HFS gage and the extended inverse code, using the temperature from the coaxial thermocouple.

In *figure 6.1* the flux as given by the HFS heat flux gage is compared to the flux as calculated by the extended inverse code from the surface and the back face temperature measurements. The effect of the noise in this case is not shown, but the black vertical bars on the graph show the band in which the noise has been observed. The calculated flux is much higher than that of the heat flux gage at the start of the run. This should not be of any concern, because the actual run starts at about 5s. The noisy temperature signal also contributes to this peak in the beginning. The peak that follows at about 5s is, however, very important and might show details not captured by the heat flux gage. One of the major uncertainties of the heat flux gages in the measurement of heat flux is that they need to be calibrated. This causes uncertainty in the sense that the heat flux used to calibrate the sensors is not always known very accurately and the same applies to the sensors used to calibrate them by.

If the peak in the figure is disregarded from *figure 6.1* the percentage difference between the results for HFS gage and the extended inverse technique, at the maximum flux is:

$$\begin{aligned}\%\ \text{Error} &= \frac{(6-5)}{5} * 100 \\ &= 20\ \% \qquad (6.1)\end{aligned}$$

The difference in the values of the heat flux obtained by the HFS heat flux gage is compared to the heat flux obtained through the numerical evaluation of surface and back face temperature measurements using the extended code in *figure 6.2*. Initially there is an offset of 0.7 W/cm^2 that increases to a maximum offset of 2 W/cm^2 after about 10 seconds. The deduced values from the new code, using the surface temperature from the Medtherm thermocouple, then start to approach those of the heat flux gage values as the run concludes.

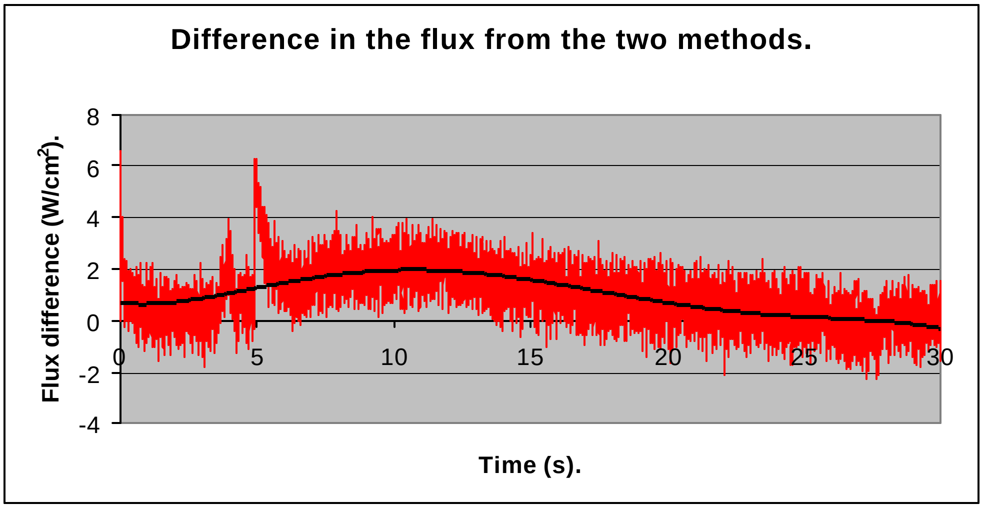

Figure 6.2 The difference in the flux measured by two methods.

6.2 Possible errors in the process of converting from voltage to heat flux.

The difference in the heat flux measurement values can be a combination of several factors. These factors will now be discussed in more detail in this section. These uncertainties range from the frequency at which the data was recorded to the errors induced in the computer code.

Measurements at 100Hz

Measurements were made at a frequency of 100 Hz. This is a fairly high frequency, but small errors might occur. This error is, however, assumed to be minimal, because the rate at which the voltage output of the thermocouple changes is assumed to be captured accurately with a sampling rate of 100 Hz. This is because the only real fluctuations in these samples are the turbulent fluctuations. No shocks were expected during these runs. Passing shocks may require a higher sampling rate. The value of 100 Hz was chosen, because the LabView program used to do the data acquisition was also used for other instrumentation, and those measurements required a sample rate of 100Hz.

Ice-bath

In the experiment, an ice-bath was used for the reference temperature of 0^0C. An error here would alter the temperature measured with the thermocouple in the blade. Good accuracy was achieved by inserting this reference thermocouple into a glass tube, filled with oil and then placing this tube into the thermos flask. The oil helped to keep a constant temperature around the thermocouple, and the glass tube prevented the thermocouple from touching the ice cubes that might cause temperature fluctuations. If a proper technique is used, the uncertainty in the reference junction temperature can be made negligibly small. [28] If the bath is not used with care serious errors can result. In these experiments extreme care was taken with the ice bath, so that the error should be negligible [28] See *figure 6.3* and *figure 6.4.*

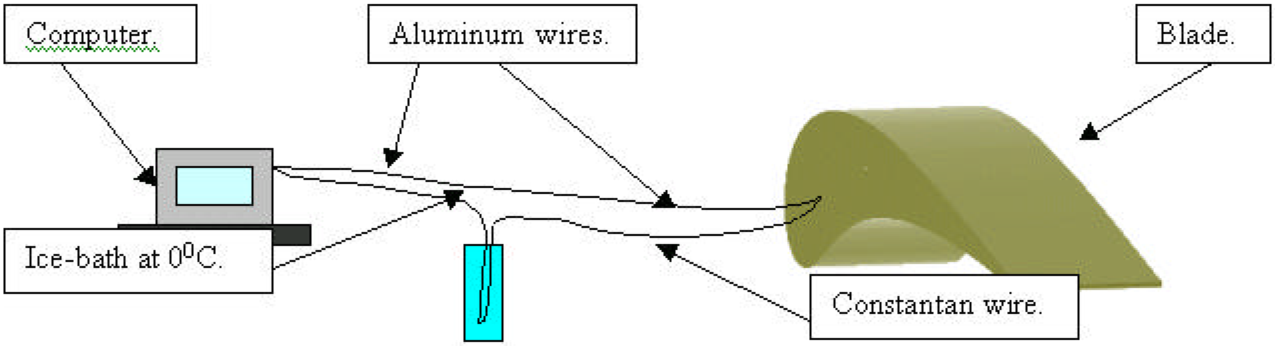

Figure 6.3 Layout of the experimental set-up.

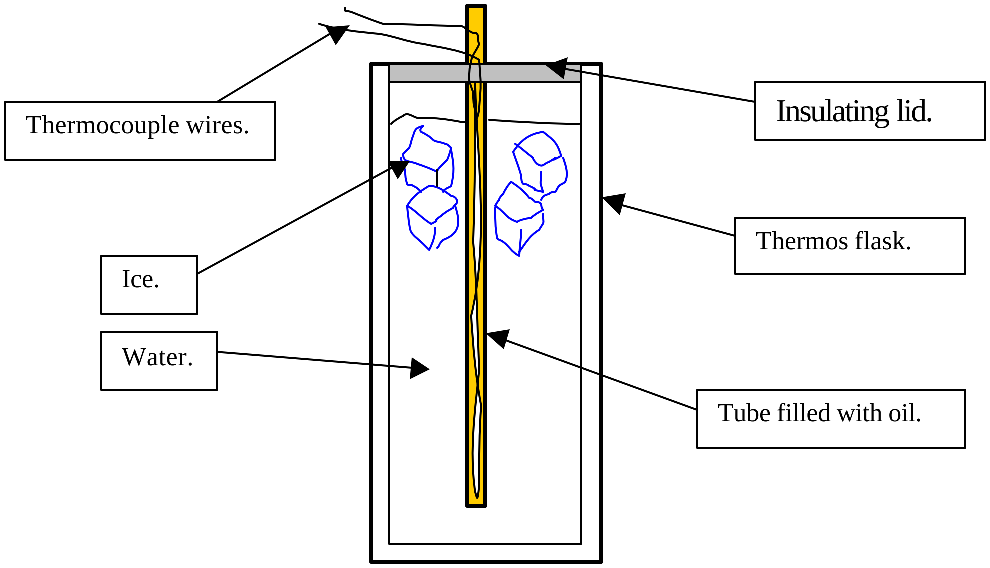

Figure 6.4 Physical ice-bath.

Calibration factor of the Medtherm thermocouple.

The calibration factor for the Medtherm thermocouple was taken as 39.6 $\mu V/^0C$. This value was supplied by the Medtherm corporation. To verify this calibration factor, a number of points of temperature versus voltage output were measured and plotted on a graph in *figure 6.5*. The slope of a linear fit through the data, revealed a value of 40.7 $\mu V/^0C$. This is very close to the value supplied by the manufacturers of the thermocouple. Most thermocouples do not behave perfectly linearly and this value might change for different temperature ranges.

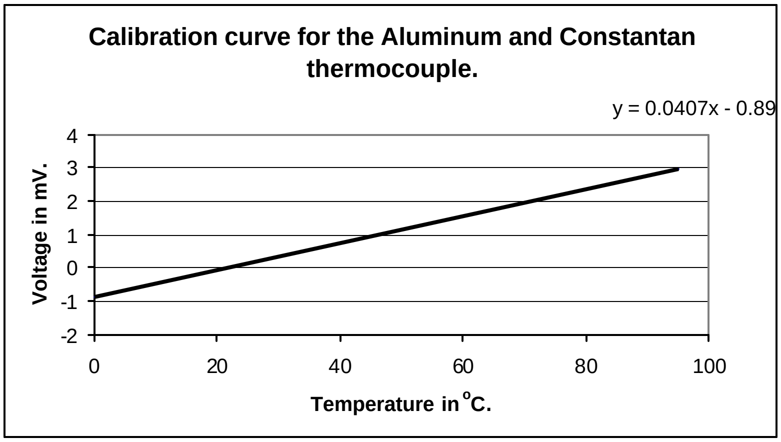

Figure 6.5 The Al/Constantan thermocouple calibration curve.

If this particular value of 40.7 μV/°C is used in the code the heat flux for the same temperature history shown in *figure 4.8* the heat flux is not altered significantly. The heat flux for a calibration factor of 40.7 μV/°C is shown in *figure 6.6*. A small difference is noticeable near the end of the run , at about 20 to 30s.

The percentage difference between the graph in *figure 6.6* and the original one calculated with a calibration factor of 39.6 μV/C°, is calculated to be 3.5%. This value grows gradually, because the numerator in the equation below becomes smaller and smaller.

$$\%error = \frac{New - Old}{Old} * 100 \tag{6.2}$$

$$\%error = \frac{11.1401 - 11.1362}{11.1362} * 100 \tag{6.3}$$

It will therefore be more convenient to look at the error at a certain point in time. In this case the point of maximum flux was considered.

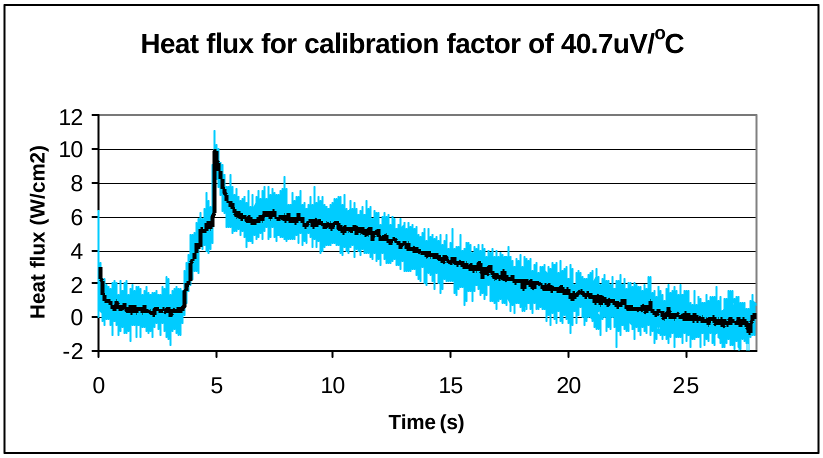

Figure 6.6 Heat flux for a calibration factor of 40.7 mV/°C

Type-K thermocouple

The type-K thermocouple used at the back face might also cause some error in the final result. There are basically two problem areas:

- First, the calibration of the thermocouple can be imperfect. The values used are built into the LabView program. Type-K thermocouples are widely used in the industry, and calibration factors for them are very accurate. This problem is thus not a dominant one.

- The fact that the thermocouple is glued to the aluminum surface creates a larger uncertainty. This uncertainty was minimized, by using an aluminum based metal epoxy. These epoxies conduct heat very well, so the assumption that the thermocouple is actually part of the solid was made.

Constant properties

The properties of most metals change with a change in the temperature. Here, the assumption was made to keep the properties constant, because of the small range of the temperature encountered. Table 6.1 shows the range of the thermal conductivity. It also shows the difference in the properties of the blade and the thermocouple. All of these differences create a margin of error. The code can, however, be improved by adding the option of variable properties. For the results in *figure 6.7* the conductivity was changed to the minimum of 155W/mK. The output looks very similar to that in *figure 6.8* where a conductivity value of 180W/mK was used.

Table 6.1 Comparing the physical properties of the blade and the thermocouple.

Aluminum	**Blade**	**Thermocouple**
Alloy	**6061**	**3003**
Density kg/m^3	2700	2720
Conductivity W/m.K	155 - 180	162
Specific heat J/kg.K	896	893

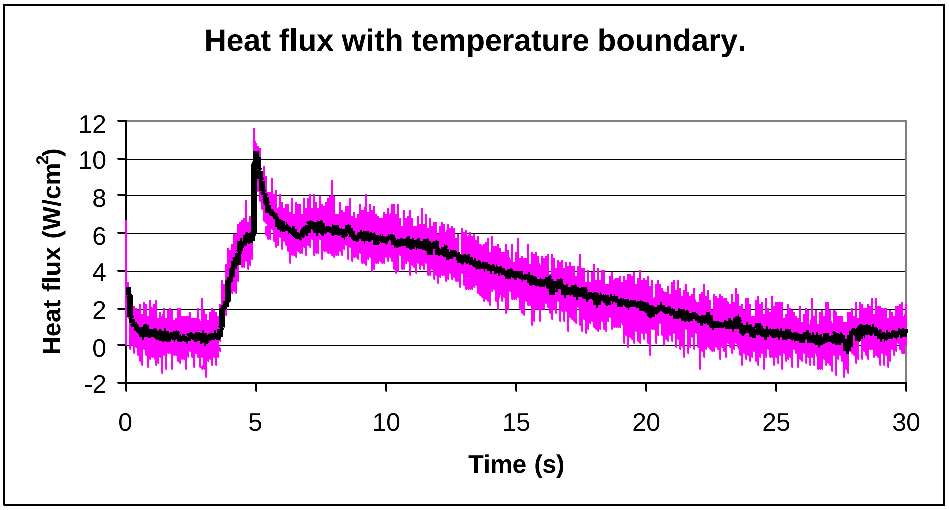

Figure 6.7 Predicted heat flux with thermal conductivity of 155 W/mK from the temperature in figure 4.14.

If the same approach is used as with the difference in the calibration factors the error in this case is calculated to be 4% at maximum flux.

$$\%error = \frac{11.582 - 11.1362}{11.1362} * 100 \qquad (6.4)$$

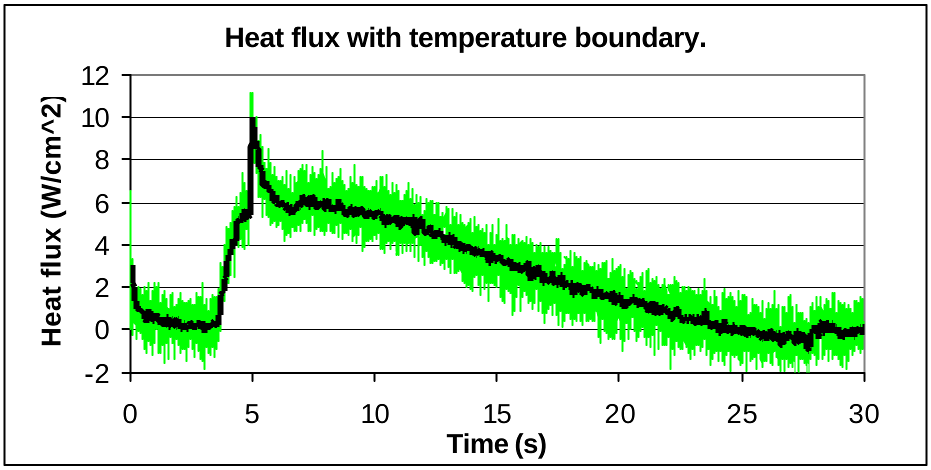

Figure 6.8 Predicted heat flux with thermal conductivity of 180 W/mK from the temperature in figure 4.14.

Errors in the code

In the inverse code itself, iteration is used to converge to some heat flux. Iteration processes do need some margin of error at which the iteration is stopped. In other words, if the answer is close enough according to the tolerance in the code, it moves on to the next time step. The code in this case, makes use of a tolerance and a sensitivity difference factor. The tolerance is used on two errors calculated in the code. The next guess in the iteration is obtained by calculating a new sensitivity matrix that is used to obtain a new temperature profile through the material. This is a non-dimensional matrix and can also induce some errors. After evaluation of these factors it was found that the results are very similar to those obtained when using the value in the original code. See chapter 3 for more details on the sensitivity matrix and the regularization parameter that is used to perturb the flux guess.

6.3 Residuals

Calculating the residuals for the Cook-Felderman technique and the inverse method as well as the measured flux from the HFS heat flux gage, the following results were obtained. Duhamel's method [19] for the integration of the flux in order to recalculate the temperature, was chosen. This is a numerical integration method. It is important to realize that it is a semi-infinite procedure. It is, therefore, expected that the temperature will diverge at larger times, from the calculated temperature. The percentage difference in the temperatures from Duhamel's method and the original measured temperature from the Medtherm thermocouple can be seen in *figure 6.9*.

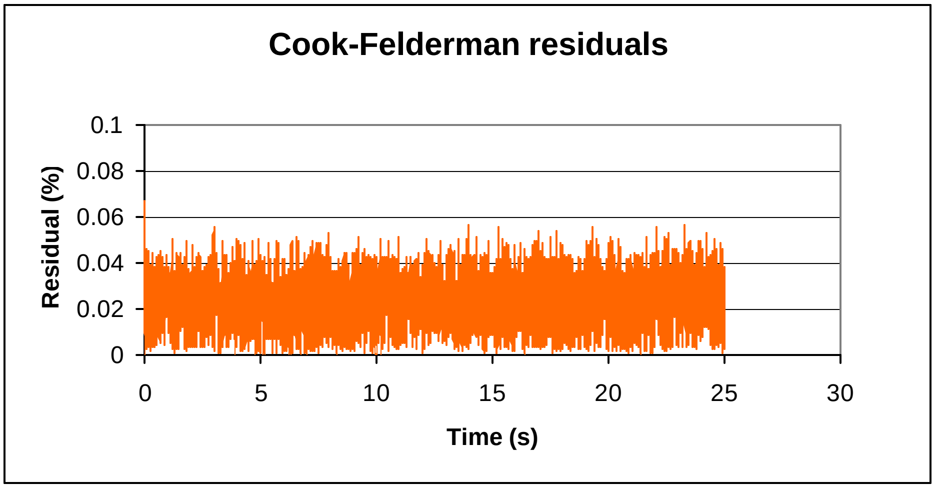

Figure 6.9 Percentage difference in the temperatures calculated with Cook-Felderman.

From this graph it is evident that the percentage difference is very small. This is also a contribution from the fact that the Cook-Felderman method is a semi-infinite one. The residuals for the inverse method are shown in *figure 6.10*. Here it is evident that the percentage of the residuals rises to a maximum of 1.3%. This rise is due to the divergence of the calculated temperature from the measured temperature. See *figure 6.12*. This divergence is also a result of the semi-infinite approach. The residuals for the HFS heat flux gage are given in *figure 6.11*. The same effect as with the inverse approach is given here. The maximum value here is, however, a little higher – 1.8%. The gradual rise in the residuals is also due the semi-infinite approach. The lower percentage of the residuals for the inverse method suggests that the inverse method is slightly more accurate for these particular temperatures and fluxes. In both cases the residuals are small which make these calculations reliable.

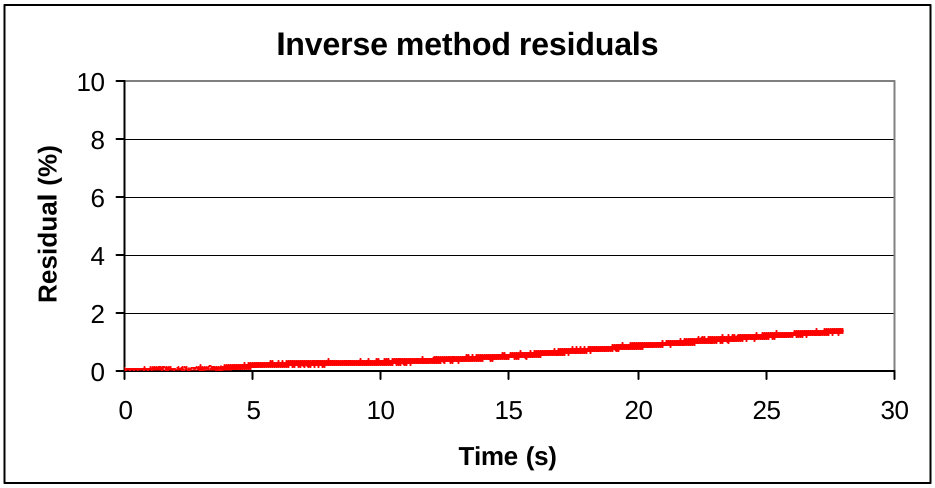

Figure 6.10 Residuals calculated for the inverse method.

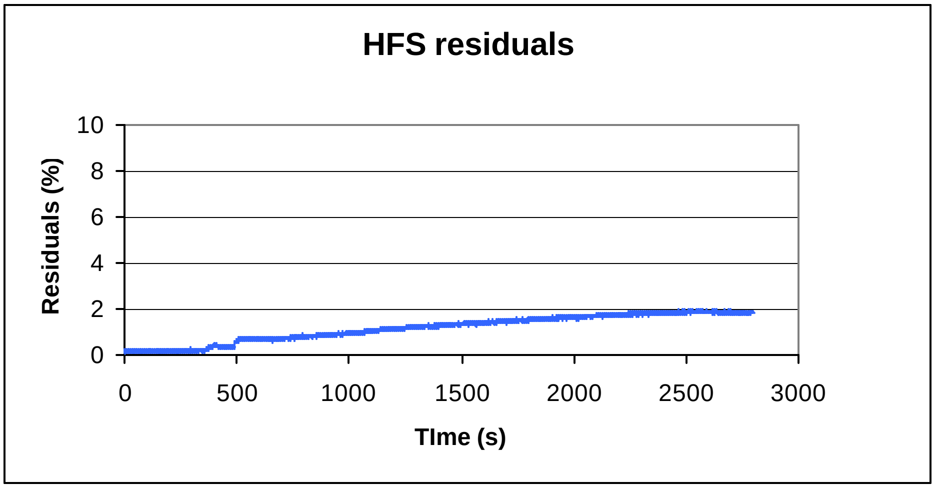

Figure 6.11 Residuals calculated for the HFS heat flux gage.

Looking at the temperature difference between the Cook-Felderman technique, the inverse method and the HFS heat flux gage can be seen in *figure 6.12*. The temperatures from the Cook-Felderman technique is very close to the original measured temperature, because of the semi-infinite approach. The measured temperature is, in fact hidden by the Cook-Felderman temperature. This is not the case for both the HFS heat flux gage and the inverse method. In both these cases a finite approach was followed.

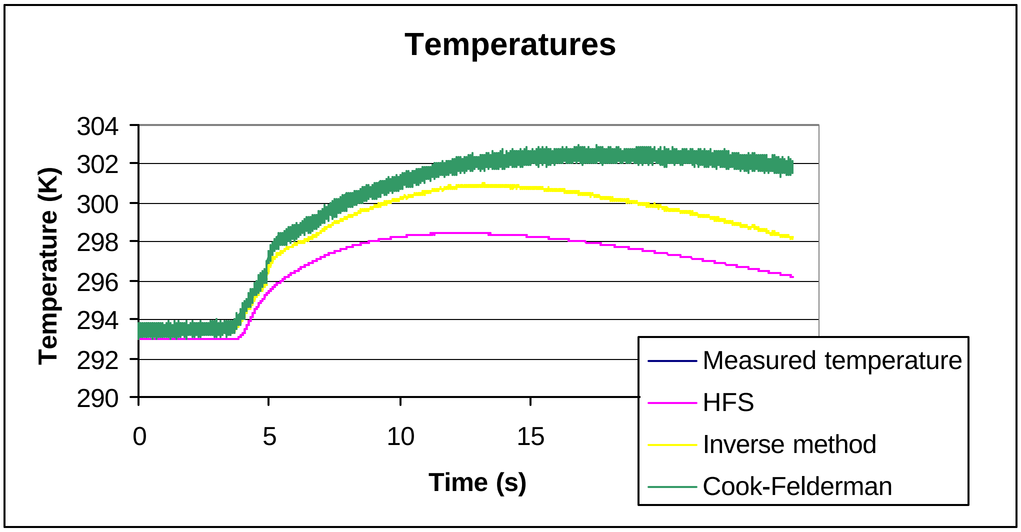

Figure 6.12 The measured temperature and the temperatures calculated with Duhamel's method for the three different cases.