AN APPROACH TO INFER THE MODERATOR TEMPERATURE OF A CANDU REACTOR FROM MEASUREMENTS INSIDE A VERTICAL FLUX DETECTOR

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ABSTRACT

This paper proposes an approach to infer the moderator temperature of a CANDU reactor from an in situ temperature measurement inside a vertical flux detector. This approach involves the reverse solution of the governing equation for heat transfer from the metallic detector under radiative heating to the outside moderator by use of a 3D code for numerical heat conduction. The underlying theoretical basis for this approach is explained and uncertainties associated with this approach when applied to the indirect measurement of moderator temperature are analyzed where possible.

INTRODUCTION

The heavy water moderator in the calandria of a CANDU reactor is credited as a heat sink in abnormal situations, such as contact between the pressure tubes and the calandria tubes. A sufficient subcooling margin for the moderator must be maintained. However, the distribution of moderator temperature over the calandria is complex, even under normal operations, because of the interaction between the incoming cooled heavy water, a flow that is based primarily on momentum, and the heat emanating from the calandria tubes, a flow that is based primarily on buoyancy. There may be regions in the calandria where the required subcooling margin cannot be maintained. Measurement of moderator temperature is desirable so that operators can be confident that an adequate subcooling margin exists during operation. If feasible, such measurements would also provide a database for validating CFD models that can predict more extensively the temperature distribution within the calandria. Direct measurements of the moderator temperature have been performed on a CANDU reactor [1, 2] in which permanent probes with temperature sensors were installed in the calandria during an outage. Recently, a method to measure the moderator temperature indirectly has been investigated [3]. Researchers measured the temperature profile along the length of the Travelling

Flux Detector (TFD) well inside a vertical flux detector tube (Figure 1). Since this Zircaloy structure is subject to intense radiative heating, an inference approach is required to obtain the temperature profile of the moderator outside the guide tube from the raised TFD-well temperature.

This paper proposes an approach to infer the moderator temperature by use of an iterative guess-and-correct process, aided with the HEATING code [4] for numerical heat conduction. While the inference method itself is generally applicable to similar problems, the uncertainty analysis associated with this approach has been performed for this specific measurement.

MATHEMATICAL MODEL FOR THE VERTICAL FLUX DETECTOR

There are a number of flux detectors that vertically transverse the calandria of a CANDU reactor. Figure 1 depicts the idealized cross section of a vertical flux detector made of Zircaloy, which has 12 detector wells inside the detector capsule. The TFD well, which is normally empty, has been identified as the location for the measuring device that will be used to infer the temperature of the moderator outside the guide tube. The gap between the guide tube and detector capsule is filled with heavy water (D_20) and is connected to the outside moderator via two small holes at one end of the guide tube. The space within the detector capsule and within the detector wells is sealed and filled with helium.

It is assumed that the movement of fluids within the detector can be neglected, since the radial dimension of the system is limiting (e.g., the outer diameter of the guide tube is only 20.828 mm). Under radiative heating, the energy deposited within the detector has to be transferred outward to the

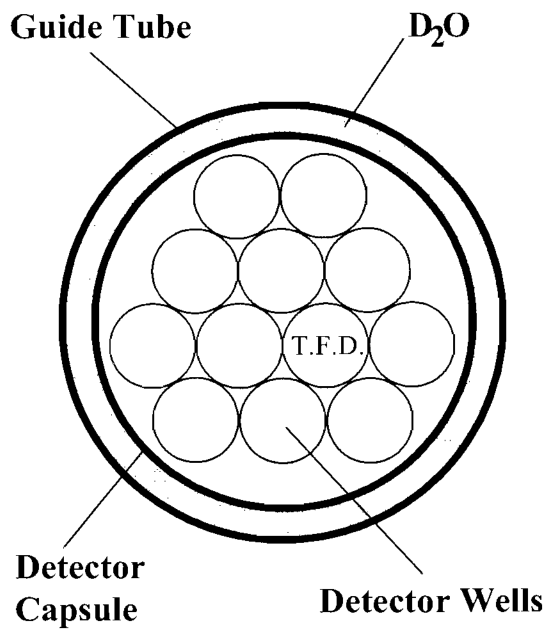

Figure 1. Cross section of a vertical flux detector inside the calandria

moderator. In this sense, the contact among the detector wells plays an important role in radial heat transfer, since Zircaloy has a much higher thermal conductivity than the helium gas that fills the free space. However, the complex nature of this stack of circular wells is not easy to solve by use of codes such as HEATING. The cross section of the detector is thus first simplified as shown in Figure 2, where the sensing device measures the average temperature (measured circumferencially) of the innermost ring. In this simplified geometry model, the circular rings are linked to each other through radial fins that simulate the effect of contact among all detector wells. The identical fins and the rings with same thickness are evenly separated. The total mass of the rings and fins is equal to that of the 12 detector wells, so that the amount of the radiative heat deposited on them is maintained. The geometric parameters of this ring-fin system can be validated against the internal heat resistance of the original stack of wells, which can be established by measurement.

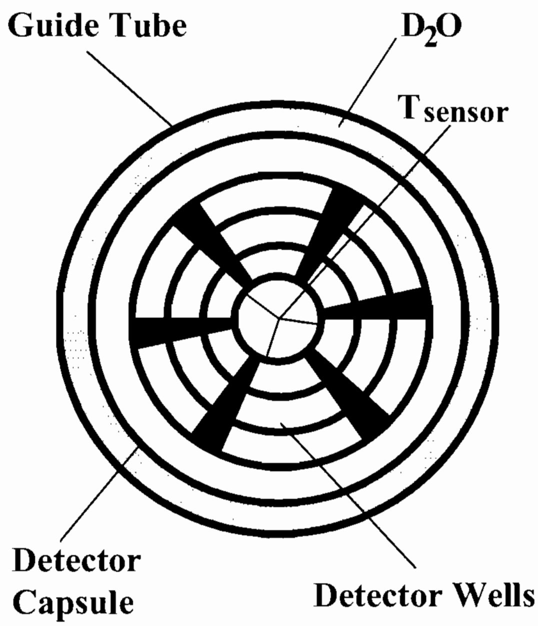

Figure 2. Geometry model for the cross section of the vertical flux detector

Axial heat transfer within the metallic structure is also important, since neither the radiative energy deposition along the detector nor the moderator temperature outside the guide tube is uniform. The resultant axial temperature attenuation cannot be ignored, since we are interested in possible regions with high moderator temperature. Furthermore, it is also necessary to consider the axial heat transfer so that we can demonstrate the effectiveness of the methodology described in this paper for use in similar problems. Therefore, the profiles of the radiative heat generation and moderator temperature along the flux detector, which will be used in the approach reported herein, are not necessarily those of the reactor calandria.

As a summary, three-dimensional steady-state heat transfer within the vertical flux detector is being modelled, which involves different materials: Zircaloy, heavy water and helium. The governing equation for heat conduction is well established in the literature, and the convective heat transfer between the guide tube and moderator occurs as the boundary condition. Radiative heat transfer across the gaps filled with helium is also considered. This model is solved numerically as one step of the inference process described below.

INFERENCE METHOD

The inference method is based on the analysis of a simple one-dimensional heat conduction problem. An infinite cylinder with radius R imposed with a uniform volumetric heat source q is immersed in a moving fluid at temperature T_f. The steady-state theoretical solution for the temperature at radius r within the cylinder is:

$$T = \frac{q(R^2 - r^2)}{4k} + \frac{qR}{2h} + T_f \tag{1}$$

where
k = the thermal conductivity of the cylinder material and
h = the convective heat transfer coefficient between the cylinder and the fluid.

Equation (1) shows that there is a linear relation between T and T_f and that a superposition of the fluid temperature can therefore be applied:

$$T_2 = T_1 + (T_{f2} - T_{f1}) \tag{2}$$

where
T_1 and T_2 are the solutions for this problem with fluid temperatures T_{f1} and T_{f2}, respectively.

For a reverse problem, i.e., with known T_2 at a given position (e.g., T_{c2} at the centre of the cylinder) but with unknown T_{f2}, the fluid temperature thus can be deduced as:

$$T_{f2} = (T_{c2} - T_{c1}) + T_{1f} \quad (3)$$

where
T_{c1} = the solution at the centre of the cylinder with the known boundary fluid temperature T_{f1}.

Equation (3) is not strictly applicable for a three-dimensional problem such as the one described in this paper, since the model is non-linear because of radiation and temperature-dependent material conductivity and since the fluid temperature and heat generation are dependent on space. Equation (3) has, however, been helpful in establishing the following formulation for three-dimensional situations:

$$T_{f2}(z) = [T_{s2}(z) - T_{s1}(z)] + T_{f1}(z) \quad (4)$$

where
z = the coordinator in the axial direction and
s = the value at the sensor position.

The accuracy of Equation (4) depends largely on the magnitude of the heat generation within the system. When the heat generation is so high that the radiative heat transfer becomes comparable to the conductive heat transfer, the blockage of the radiative heat transfer from the inside to the outside of the system because of the rings also becomes important. Figures 3 and 4 show the effect of the heat generation on the fluid temperature obtained with Equation (4). Here the known boundary fluid temperature, $T_{f1}(z)$, is taken as uniform (20°C) along the axial direction. The heat generation is distributed axially over a length of 700 cm within the calandria as a sinusoidal function with the maximum values of 0.03 cal/(s.cm^3) and 1.2 cal/(s.cm^3) at the centre of the calandria, respectively. The temperature profile at the sensor position, $T_{s1}(z)$, corresponding to the known fluid temperature, $T_{f1}(z)$, is solved beforehand from the model established in the previous section. The temperature profile, $T_{s2}(z)$, is also solved first by use of an assumed real fluid temperature profile, $T_{f2A}(z)$, to represent the measurement. The inferred fluid temperature by solving Equation (4) once (the "Inferred Fluid Temperature1" in the figures), is very close to the assumed real fluid temperature, $T_{f2A}(z)$, for the low heat-generation case, although there is a large discrepancy for the high heat-generation case.

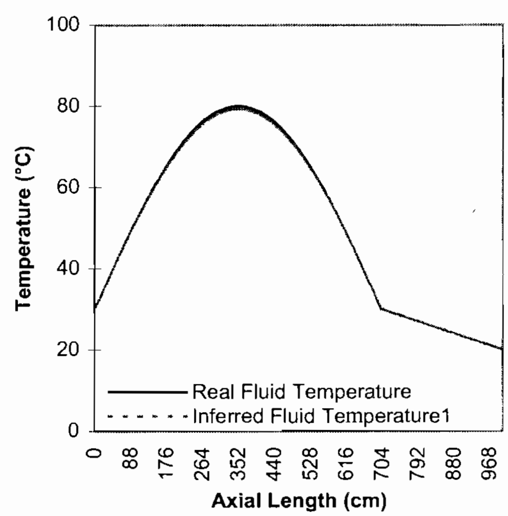

Figure 3. Inferred fluid temperature with a sinusoidal profile of heat generation peaked at 0.03 cal/s.cm^3

However, for the latter case, which uses the latest inferred $T_{f2}(z)$ as the known (i.e., the guessed) $T_{f1}(z)$, repeating the above process can make the inferred fluid temperature attain the assumed real fluid temperature, $T_{f2A}(z)$, within a few iterations (Figure 4). Because of the heat blockage by the structure inside the detector capsule, the following relations generally hold at any location in the axial direction, z_0:

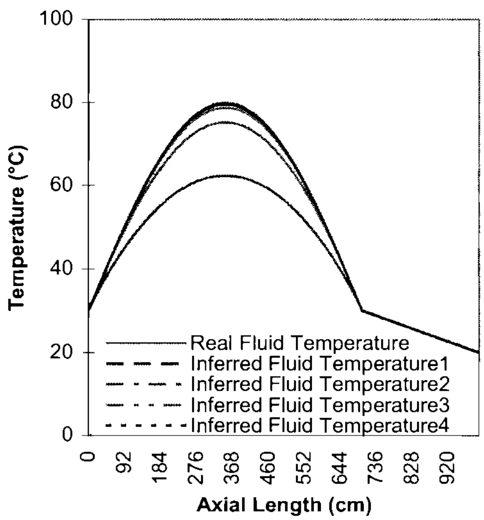

Figure 4. Inferred fluid temperatures with a sinusoidal profile of heat generation peaked at 1.2 cal/s.cm^3

$$T_{s2}(z_0) - T_{s1}(z_0) \leq T_{f2}(z_0) - T_{f1}(z_0) \qquad (5)$$

if $T_{f1}(z_0) \leq T_{f2}(z_0)$ and

$$T_{s1}(z_0) - T_{s2}(z_0) \leq T_{f1}(z_0) - T_{f2}(z_0) \qquad (6)$$

if $T_{f1}(z_0) \geq T_{f2}(z_0)$.

Equations (5) and (6) guarantee that the inferred boundary fluid temperature converges to the real boundary fluid temperature in an iterative process when Equation (4) is used to calculate the inferred fluid temperature.

Figure 5 illustrates another inference process, where the profile of the boundary fluid temperature is more complicated and tolerates little axial attenuation during the inference. Here, a uniform heat generation of 1.0 cal/s.cm^3 is imposed within the calandria, and the guessed boundary fluid temperature used for the first inference is a uniform profile of 20°C.

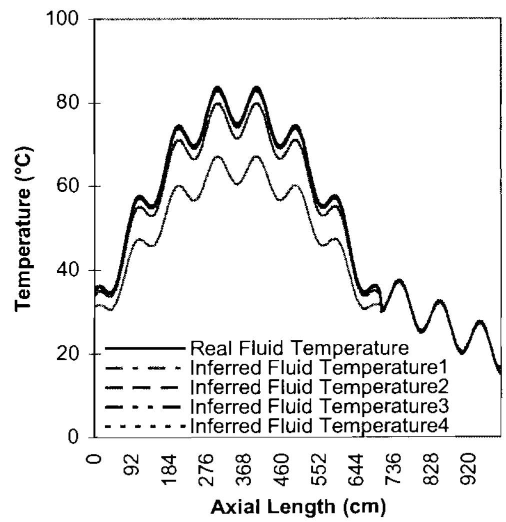

Figure 5. Inferred fluid temperatures with a uniform profile of heat generation at 1.0 cal/s.cm^3

It is proposed that, after the measurement, the temperature profile along the TFD well serves as the $T_{s2}(z)$ function in Equation (4). The temperature profile of the moderator outside the guide tube can then be inferred by following the iterative process described below:

1 Assume an initial fluid temperature profile $T_{f1}(z)$.

2 Solve for the temperature profile $T_{s1}(z)$ under the guessed temperature profile, $T_{f1}(z)$.
3 Use Equation (4) to calculate the inferred fluid temperature profile $T_{f2}(z)$.
4 Make $T_{f1}(z) = T_{f2}(z)$ and repeat Steps 2, 3, and 4 until the required accuracy for the fluid temperature is achieved.

ACCURACY OF THE APPROACH

Theoretically, the approach that is proposed in this paper could accurately infer the temperature profile of the moderator outside the guide tube from the measured TFD well temperature. This reverse solution is achieved when the iterative process described in the last section is carried on for a sufficient number of iterations. The actual accuracy of this method is, however, dependent on the complexity of the specific problem being considered.

There are three sources of uncertainty generally associated with this approach: the overall model, the measurement, and the heat generation used during the inference. For this problem, the model involves the simplified geometry and the physical principles applied to it, which should be validated in test rigs before the indirect measurement is performed. Since the thermocouple itself is heated by gamma rays during measurement, it is important to correct the error induced by this factor. Fortunately, it has been proved that, if the thermocouple is properly selected to resist the radiative heating, the effect of the gamma rays on the thermocouple could be neglected [1, 2]. As for the radiative heat generation, there are a few analytical and numerical tools that can be used to calculate the distribution of radiative energy deposition within the calandria with reasonable confidence. Each of the above three aspects deserves a more comprehensive study, which is beyond the scope of this paper. Instead, this paper continues with the theoretical analysis, which will focus particularly on the effect of an inaccurate heat generation used during the inference on the accuracy of the inferred fluid temperature.

For the previous simple one-dimensional problem, the temperature at any given position $r = R_a$ is obtained by solving the following:

$$T_a = q\left(\frac{R^2 - R_a^2}{4k} + \frac{R}{2h}\right) + T_f . \qquad (7)$$

The temperature at the same position but with a different fluid temperature, T_{f1}, is:

$$T_{a1} = q\left(\frac{R^2 - R_a^2}{4k} + \frac{R}{2h}\right) + T_{f1} . \qquad (8)$$

Subtracting Equation (8) from Equation (7) leads to, after re-arrangement:

$$T_f = (T_a - T_{a1}) + T_{f1} . \qquad (9)$$

This is the basic equation derived in the last section for a reverse problem, in which the fluid temperature T_f is to be solved from the known temperature T_a inside the cylinder. Here the temperatures T_{f1} and T_{a1} can be viewed as a reference fluid temperature and as the solution of the temperature at the same position as for the temperature T_a from this reference fluid temperature, respectively. If there is an inaccuracy of the heat generation involved during the solution of the temperature T_{a1}, namely $(1 - x)q$ is used instead of q in

Equation (8), an inaccurate solution is therefore obtained:

$$T_{a1}^{x} = (1-x)q\left(\frac{R^2 - R_a^2}{4k} + \frac{R}{2h}\right) + T_{f1}, \quad (10)$$

which results further in an inaccurate inferred fluid temperature when applied in Equation (9):

$$T_f^x = (T_a - T_{a1}^x) + T_{f1}. \quad (11)$$

The deviation of the inferred fluid temperature from the real fluid temperature can be calculated from Equations (9) and (11):

$$T_f^x - T_f = T_{a1} - T_{a1}^x \quad (12)$$

namely, from Equations (8) and (10):

$$T_f^x - T_f = xq\left(\frac{R^2 - R_a^2}{4k} + \frac{R}{2h}\right). \quad (13)$$

Equation (7) can be re-arranged as:

$$T_a - T_f = q\left(\frac{R^2 - R_a^2}{4k} + \frac{R}{2h}\right) \quad (14)$$

and then combined into Equation (13), leading to:

$$\frac{T_f^x - T_f}{T_a - T_f} = x. \quad (15)$$

In Equation (15), $T_a - T_f$ is the rise in temperature at position $r = R_a$ inside the cylinder due to the internal heat source q, as compared to $T_a - T_f = 0$ if there is no heat source. The left-hand side of Equation (15) is the relative error of the inferred fluid temperature in terms of the above temperature rise, which is equal to the relative error x in the heat generation. From Equation (14), if the heat generation is constant, the temperature rise will be the same no matter the level of the fluid temperature. As a result, the absolute error of the inferred fluid temperature $T_f^x - T_f$ will be constant at a given error of a given heat generation no matter how low the fluid temperature is. Therefore, consideration of only Equation (15) is not adequate to analyze the effect of the inaccurate heat generation on the inferred fluid temperature. A relation directly linking the error in the inferred fluid temperature to the real fluid temperature is needed, which can be obtained by first transforming Equation (15) to:

$$T_f^x - T_f = x(T_a - T_f) \quad (16)$$

then dividing the resulting equation by the fluid temperature:

$$\frac{T_f^x - T_f}{T_f} = x\left(\frac{T_a}{T_f} - 1\right) \quad (17)$$

where
T_a/T_f is always greater than unity due to the internal heat source.

Equation (17) indicates that, if $T_a/T_f > 2$ (i.e., the temperature rise, $T_a - T_f$, is larger because of the heat generation than the fluid temperature itself), the inaccuracy in the heat generation used during the inference will greatly influence the inferred fluid temperature. Otherwise, if $T_a/T_f < 2$, a reduced extent of the inaccuracy is to be inherited by the inferred fluid temperature, which is better than what is originally expected from the inference process. On the other hand, Equation (17) shows that, at a given ratio of T_a/T_f, the relative error in the inferred fluid temperature is always in linear relation with the error in the heat generation no matter how large the latter is. This means that the extent of enlargement or reduction of the inaccuracy in heat generation during inference will remain the same at a given ratio of T_a/T_f no matter how serious the uncertainty in the heat generation.

DISCUSSION

The foregoing theoretical analysis was based on the linear assumption between the cylinder temperature and the heat generation. However, in the actual flux detector, as stated before, there is a non-linearity in the relationship between temperature and heat generation. Nevertheless, over a small range of heat generation, the linear relation can be reasonably assumed, especially for the low temperature range in the present problem. Therefore, if a small uncertainty in the heat generation has to be taken into account during the inference with the flux detector, the previous theoretical discussions about the effect of the inaccuracy in the heat generation on the accuracy of the inferred fluid temperature should still apply.

Two-dimensional parametric studies on the fluid temperature and heat generation have been conducted to verify the applicability of the theoretical conclusion to the actual non-linear detector system. These two key parameters determine the ratio of sensor temperature to fluid temperature, which in turn indicates whether the error in the heat generation is to be amplified during the inference process. These parametric studies are based on the overall model, which requires solid validation that is not yet completed. Any quantitative discussions here should thus be considered as inconclusive and should serve only as demonstrations of applying the uncertainty analysis of inaccurate heat generation to this problem. Figure 6 depicts the effect of heat generation on the inference of fluid temperature at a given real fluid temperature and a given error in the heat generation. As the heat generation increases, the predicted sensor temperature and the ratio of sensor to real fluid temperature increase almost linearly. As a result, the fluid temperature inferred from this sensor temperature has an increscent error, which is smaller in the absolute value than the given error in heat generation when the ratio of sensor to real fluid temperature is less than about 2, but with an opposite sign. The opposite sign of the errors in the heat generation and inferred fluid temperature is necessary to maintain the same sensor temperature. For example, if the heat generation used during the inference is less than its actual value, the inferred fluid temperature has to be higher than the real fluid temperature for compensation in order to keep the same sensor temperature level.

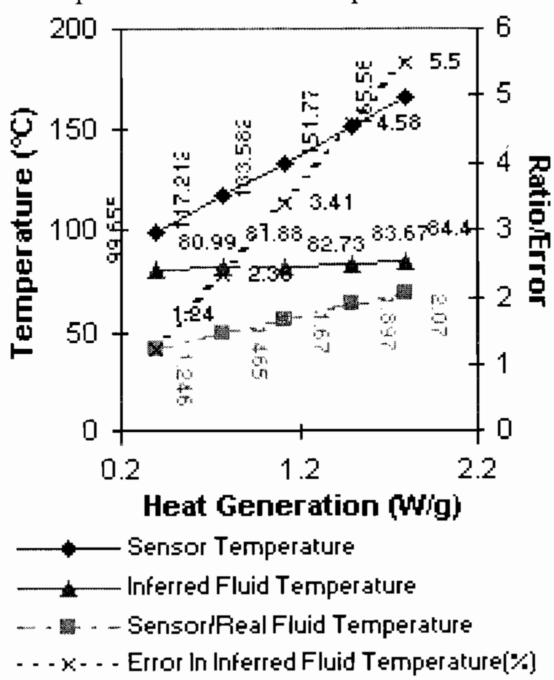

Figure 6. Effect of heat generation on the inference of fluid temperature (Real fluid temperature is 80°C with a –5% error in heat generation.)

Figure 7 further verifies the theoretical conclusion over a presumed wide range of the uncertainty in heat generation. Even if the error in heat generation is large, the resultant error in the inferred fluid

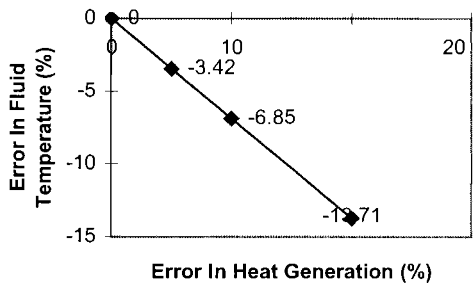

Figure 7. Effect of inaccuracy in heat generation on the accuracy of inferred fluid temperature (Ratio of sensor/real fluid temperature = 1.67 at a real fluid temperature of 80°C and heat generation at 1.11W/g.)

temperature still demonstrates an almost linear relation with the error in heat generation at a given ratio of sensor to real fluid temperature. The effect of real fluid temperature on the ratio of sensor temperature to real fluid temperature was studied with the maximum possible level of radiative heat generation rate of the CANDU reactor at full power (1.11W/g [5]). The preliminary results showed that, if the fluid temperature was greater than about 40°C, the ratio of sensor to real fluid temperature will be less than 2. This critical temperature is well below the inlet temperature (51°C) of the moderator of this CANDU reactor at full power. Therefore, under the whole range of radiative heat generation and moderator temperature within the calandria of the CANDU reactor at full power, the inaccuracy in inferred moderator temperature due to the inaccuracy in heat generation is limited within the extent of the uncertainty in heat generation. Once again, this argument is inconclusive, which is based on the overall model in need of solid validation.

CONCLUSION

An approach to infer the moderator temperature of a CANDU reactor from in situ temperature measurement inside a vertical flux detector is proposed. It involves reverse solving the governing equation for heat transfer from the metallic detector under radiative heating to outside moderator, using a 3D code for numerical heat conduction. Underlying theoretical basis for this approach is explained, and where possible, uncertainties associated with this approach when applied to the indirect measurement of moderator temperature are analyzed.

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