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Integral boundary layer heat transfer modeling for Tehran Research Reactor

Kazem Farhadi*

Engineering Science Research Group, Nuclear Science Research School, Nuclear Science and Technology Research Institute, AEOI, P.O. Box 11365 3486, Tehran, Iran

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ABSTRACT

In the present work the validity of applying the Boussinesq approximation in the analysis of natural convection heat transfer along nuclear fuel plates with large coolant channel aspect ratios is evaluated. The Boussinesq approximation is introduced into the integral boundary layer equations governing the system to describe the velocity and temperature distributions of the coolant in the cooling channels. The fuel plate temperature is related to the adjacent coolant fluid temperature by a fundamental law in conduction heat transfer. Air and water are considered as fluids. The coolant flow is assumed to be fully developed which is a convenient assumption for coolant channels having large aspect ratios. Obtained results indicate that the Boussinesq approximation is merely applicable over a limited range of coolant channel outlet fluid temperatures. The use of this approximation produces conservative estimation of the critical plate power for air flow and non-conservative estimation of the critical plate power for water flow.

1. Introduction

Many areas of applied engineering benefit from natural convection heat transfer. Nuclear research reactors are cooled after an emergency shut-down or an accident by natural convection mechanism. The flow is a buoyancy-induced motion resulting from body forces acting on density gradients which in turn arise from temperature and/or mass concentration gradients in the fluid.

The problem of cooling heated vertical parallel plates by natural convection has drawn considerable attention. This is primarily due to the interest initiated within the electronics industry. Elenbaas (1942) was the first one who showed that the Nusselt number (Nu) is proportional to the channel Rayleigh number (Ra). The problem of symmetric and asymmetric heating of the plates was studied by Aung (1972). He showed that the thermal development length is independent of the Prandtl number (Pr). This was rather an unexpected result due to its distinction from that of forced convection where it is well-known that the ratio of the development length for velocity and temperature is a function of Prandtl number. Later on Ramanathan and Kumar (1991) showed that Aung's result is valid only in the range of aspect ratio where axial diffusion, not taken into account for in Aung's model, is no longer significant ($L/b \geq 15$), however. As reported by Ramanathan and Kumar (1991), Aung et al. (1972) found that at these relatively high aspect ratios and corresponding low Rayleigh number, the flow may be considered to be fully developed along most of the channel. The experiments of Wirtz and Stutzman (1982) agree well with the analytical model developed by Aung. For natural circulation of air through parallel plate channels, there exists a rather large amount of data in the literature. A few data exist for water flow and the data available for air flow are limited to system configurations where the aspect ratio (plate length to gap width ratio) is less than 100 and for Rayleigh number greater than 0.1, however. It is important to note that the analytical models and experimental data mentioned within the literature were developed and obtained for the Boussinesq flow conditions, respectively. The Boussinesq approximation assumes the fluid properties are constant except density in the momentum equation when it directly affects the buoyancy force. Therefore the results obtained are limited to processes where the system outlet to inlet coolant temperature (temperature ratio) is relatively low. Under the low coolant flow and heat transfer rates this restriction is met and the Boussinesq approximation is a good approach. For physical situations where heat transfer rates are relatively high the validity of the Boussinesq approximation must be reassessed.

The Tehran Research Reactor (TRR) like many other research reactors is designed to generate high neutron fluxes. The TRR uses metallic plate-type fuel element. The compact cores within an MTR such as the TRR typically comprised fuel elements made up of several closely-spaced thin parallel fuel plates. The plate fuel is usually arranged in either flat (low enriched fuel) or annular geometries (high enriched fuel) within the fuel elements.

The physical system, Tehran Research Reactor primary cooling system, to be analyzed is shown in Fig. 1. It consists of several

* Tel.: +98 21 88221055; fax: +98 21 88221119.
E-mail address: kfarhadi@aeoi.org.ir.

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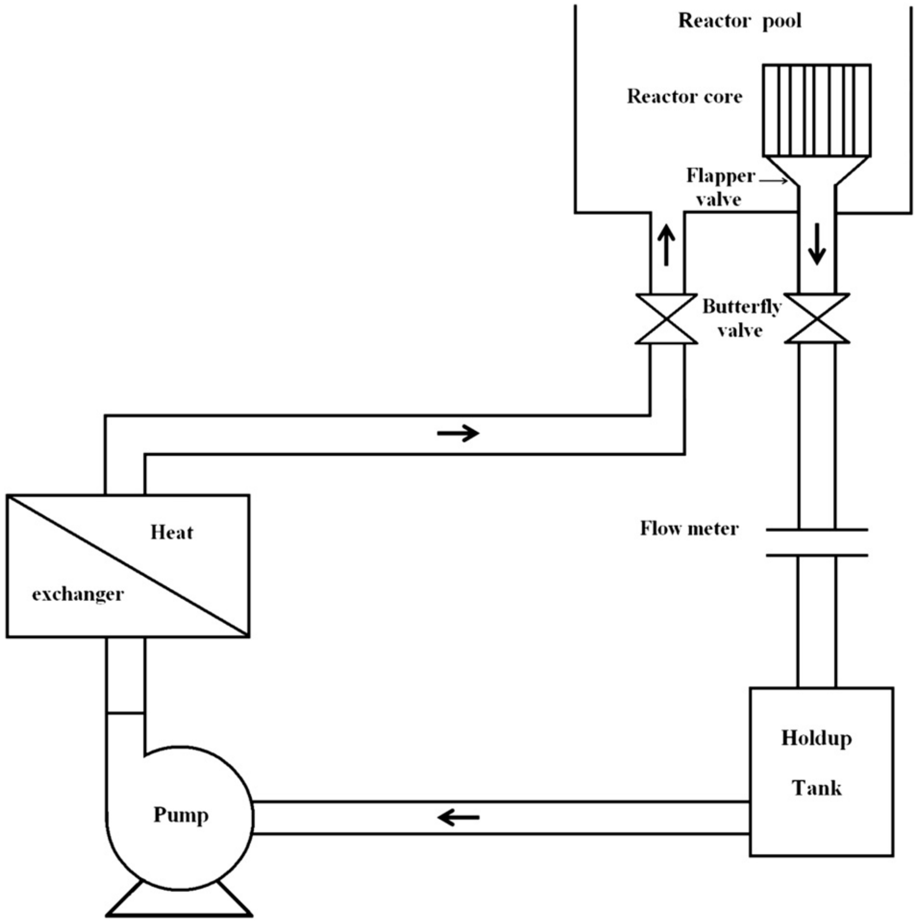

Fig. 1. Primary cooling system of TRR.

sections representing the centrifugal pump, heat exchanger, reactor pool, reactor core, orifice, hold-up tank, valves, and connecting piping. Tehran Research Reactor is a 5 MW_{th} pool-type reactor with MTR type fuel elements of low enriched uranium (LEU). The reactor is cooled and moderated with light water. The core consists of standard fuel elements (SFE) as well as control fuel elements (CFE). The SFE consists of 19 fuel plates while the CFE is of the same size and uses 14 fuel plates. The coolant is gravity driven through the reactor core grid plate into a hold-up tank and then returns back into the reactor pool by a centrifugal pump through a heat exchanger.

In the present work the issue of the Boussinesq flow along nuclear fuel plates is addressed. The method of assessment is to calculate the heat transfer process along a typical fuel plate coolant channel using the Boussinesq model developed below. Results obtained are then used to assess the assumption implied in the Boussinesq approximation. As a consequence, a maximum coolant channel outlet fluid temperature is identified (for both air and water flow conditions) above which the Boussinesq model is necessarily inappropriate.

2. Mathematical modeling

Among the existing methods, an integral boundary layer method is employed. The system governing equations is then developed by applying the Boussinesq approximation. This approximation was selected rather than using an existing model, because of the ease in applying the technique and interpreting the results.

Systems with $(L/b \geq 50)$ are only considered in the present analysis. Thereby limiting the analysis to coolant channels where the flow may be assumed to be fully developed. Also, the flow is considered to be laminar which a valid assumption is for $(\mathrm{Pr}Gr_L \leq 10^{10-12})$. This is reported by Miyamoto et al. (1982).

Thermal diffusion in the flow direction is neglected. This is due to the boundary layer flow assumption. Ramanathan and Kumar (1991) have shown that this to be a reasonable approach for $(L/b \geq 15)$. The integral boundary layer equations are written in the following paragraph in Cartesian coordinates. The *x*-direction is the direction of coolant flow along the channel (parallel to gravity line) and the *y*-direction is the outward direction normal to the plate and *z*-direction is perpendicular to the paper.

$$\frac{\mathrm{d}}{\mathrm{d}x}\int_0^l \rho u \mathrm{d}y = 0 \tag{1}$$

$$-\frac{\mathrm{d}}{\mathrm{d}x}\int_0^l \rho u^2 \mathrm{d}y - \tau_w - \int_0^l \rho g \mathrm{d}y - \frac{\mathrm{d}p}{\mathrm{d}x} l = 0 \tag{2}$$

$$\frac{\mathrm{d}}{\mathrm{d}x}\int_0^l \rho c_p u (T - T_{in}) \mathrm{d}y - q'' = 0 \tag{3}$$

Where l is half-width between a pair of parallel plate b is the distance between the plate-to-plate and L is the height of the plates along the vertical direction (direction of gravity). The equations of