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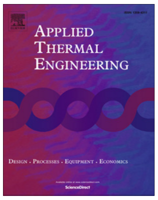

Research Paper

The effects of natural and mixed convection on heat transfer across adjacent micro-channels, in extreme pressure and temperature conditions

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HIGHLIGHTS

- Heat flux data across multi-foil insulation pack at high pressure and temperature.
- Buoyancy effects important across horizontal micro-channels less than a mm wide.
- Even small angles of inclination substantially enhance cross-channel heat transfer.
- Temperature data suggest that inclination causes reversal of imposed through flow.
- Preliminary CFD simulations confirm inclination effects for no through flow.

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ABSTRACT

This abstract summarizes a mainly experimental investigation of heat transfer across an insulation pack specimen used to protect the upper surface of the Hot Box Dome of an advanced gas cooled nuclear reactor from the hot gas above it, under actual operating conditions. The pack consists of multiple stainless steel layers forming narrow channels, less than 1 mm wide between them. The facility developed, can operate at pressures of 40 bar, temperature differences across the insulation pack of up to 500 °C, with and without flow through the pack channels and at horizontal and inclined orientations. Measurements led to the calculation of the effective thermal conductivity and also the mapping of the temperature variation across the pack for a range of flow rates, and also for angles to the horizontal of up to 30°. The effective conductivity data show how, under these extreme pressure and temperature conditions, the rate at which thermal energy is transferred to the lower, cold side, of this multi-channel pack, depends on the Rayleigh and Reynolds numbers at different angles of inclination. The corresponding local temperature measurements advance understanding of the local thermal characteristics and suggest the presence of strong flow structures. The most striking finding is the strong influence of buoyancy for all flow rates investigated, even for the horizontal cases. Tests at inclined orientations suggest the presence of flow reversal. Complementary conjugate heat transfer numerical analysis, using a simplified two-dimensional representation of the pack, has also been carried out. For the inclined case the computed flow features are consistent with those suggested by the local temperature data.

1. Introduction

This experimental investigation considers conjugate heat transfer that takes place across insulation packs, which consist of a set of multiple parallel micro channels formed between adjacent metallic foils, when exposed to extreme pressures, and with a high temperature difference across them. The motivation arises from the fact that such packs are used in advanced gas cooled nuclear reactors (AGR), to protect the Hot Box Dome which, as shown in Fig. 1, is used to separate the hot gas that emerges from the fuel cooling passages from the cooler gas in the region around the core. The primary objective of these experiments has been, through measurements of the temperature difference across the pack and of the thermal energy supplied to it, to determine its thermal conductivity at a horizontal orientation which would correspond to the location at the center of the dome and also with the pack inclined to the horizontal at angles of up to 30°, which covers the full range

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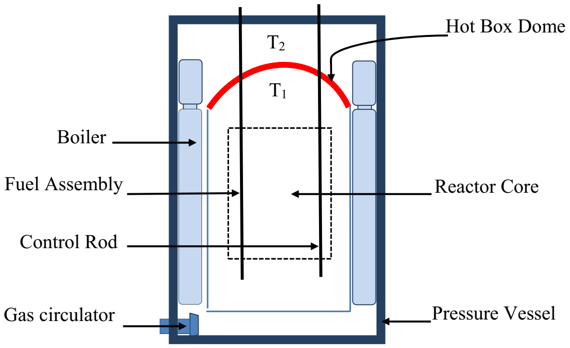

Fig. 1. Schematic diagram of an Advanced Gas Cooled Reactor.

of off-center locations, and also for a range of flows of hot gas through the pack. The latter will correspond to the reactor gas which leaks into the narrow inter-layer passages and is driven from the center of the dome outwards. A further objective of this research has been, through temperature measurements across the pack, to try and understand the flow and thermal developments under the different operating conditions. Numerical simulations of a simplified two-dimensional version of the insulation specimen have also been produced, to help with the second objective. Depending on the combination of angle of inclination and through-flow, the dominant mode of heat transfer across the micro-channels is consequently expected to vary from heat conduction to natural, mixed and possibly forced convection.

In consequence of the novelty of the experimental investigation to be reported here, there appears to be little in the literature, in terms of fundamental studies, with direct bearing on the present subject matter. Nonetheless, there are studies of related, but simpler, geometries, namely flows over isolated heated flat plates, and convective heat transfer in channels and cavities. We therefore take a look at such flows with the aim of identifying physical phenomena that bear some relation to the features found in the multiple-plate reactor insulation and which are to be discussed later in the paper. Here horizontal and inclined flows are considered. The focus is on laminar flow and on studies with thermal boundary conditions akin to those imposed here, i.e. 'stable' situations where flows are heated from above or cooled from below. Where such works exist, there is an emphasis on experimental studies. As original sources are cited, it will become clear that parts of the present literature review are of a somewhat historical nature, this being a direct consequence of the period during which a number of pioneering studies were undertaken (although efforts have been made to access the most recent editions of secondary sources). The final part of the review examines the extremely limited body of work with a more immediate connection to the present investigation.

Of all the flow and heat transfer situations to be considered here, free convection over an isolated horizontal flat plate is the most completely documented. Much of the canon of experimental work on the subject is collected in classical heat transfer textbooks. A good example is Holman [1] who includes a chapter on natural convection, paying particular attention to the empirical correlations advanced by various investigators. Incropera et al. [2] adopt a similar approach. Other textbooks include that by Bejan [3] which provides a good coverage of scaling analysis, although the focus is upon vertical external flows where the boundary layer approximations are applicable, while similarity solutions form the principal subject matter of Cebeci [4]. Jaluria [5] gives a more specialized treatment which concentrates on natural convection.

As noted above, current interest relates to the stable horizontal plate configuration. An early correlation for laminar free convection air flow over downward-facing heated square and rectangular plates was advanced by Fishenden and Saunders [6]:

$$Nu_\delta = C(Gr_\delta Pr)^n \tag{1}$$

where $C = 0.25$ and $n = 0.25$. McAdams [7] subsequently revised the value of C to 0.27.

$$Nu_\delta = \frac{h_\delta \delta}{k}; \quad Gr_\delta = \frac{\beta g(T_H - T_C)\delta^3}{\nu^2} \tag{2}$$

Here T_C corresponds to the free-stream temperature (frequently denoted 'T_∞'). The product $Gr_\delta Pr$ is also known as the Rayleigh number, Ra_δ. Eq. (1) is valid for $3 \times 10^5 \leqslant Ra_\delta \leqslant 3 \times 10^{10}$. Fishenden and Saunders specified the characteristic length scale, δ, as either the side of a square test specimen or, in the case of a rectangular specimen, the average side length. In a refinement of this formulation, Goldstein et al. [8] proposed that δ for a rectangular plate or other horizontal surface should be evaluated as the ratio of A, the surface area to the perimeter, P. In the present work, however, because only two of the four sides of the insulation pack layers are open to the flow, it seems appropriate to replace P by $2L$, where L is the side length of the square test specimen (hence $\delta = L/2$; in subsequent comparisons made with Eq. (1)).

Turning next to imposed flow over a heated plate, the thermal-hydraulic regime becomes one of 'mixed', or combined forced and free convection (assuming that conditions are not such that a wholly forced convection regime obtains). Lin et al. [9] provide a summary of analytical and numerical works on the subject. In a rare experimental study, Wang [10] reported results for air flows over both upward- and downward-facing horizontal heated plates in the free, mixed, and forced convection regimes. In both orientations there are two asymptotes: one where the Nusselt number becomes a function of Grashof number only (in the free convection, relatively low Reynolds number regime), and the other where the Nusselt number depends only on the Reynolds number (in the forced convection, or relatively low Grashof number regime). In particular at high Grashof numbers the local Nusselt number-Grashof number relationship is found to have the same exponents as those in pure free convection ($n = 1/4$ for laminar downward-facing case, cf. Eq. (1), and $n = 1/3$ for turbulent upward-facing). In the upward-facing case the local Nusselt number at a given Grashof number and increasing Reynolds number asymptotes fairly smoothly through the mixed convection regime, to join the pure forced convection limit. For the heated downward-facing plate, heat transfer levels can be impaired with Nusselt numbers in the mixed convection regime exhibiting a significant 'dip' below forced convection values.

Experimental studies of inclined flat plate free convection heat transfer have tended to characterize the regime in terms of plate inclination to the vertical. Fujii and Imura [11] used water as the working fluid and conducted experiments on both downward- and upward-facing heated plates. The thermal boundary condition was between uniform wall heat flux and uniform wall temperature. Heat transfer correlations are presented in terms of Grashof number, Eq (2), with T_H evaluated at the plate mid-height. In the downward-facing case the Nusselt number could be correlated as

$$Nu_\delta = 0.56(Ra_\delta cos\theta)^{0.25} \tag{3}$$

where θ is the plate angle to the horizontal. The expression is valid for $10^5 \leqslant Ra_\delta \leqslant 3 \times 10^{11}$ and $\theta \leqslant 87°$. (It is noted that the coefficient for a vertical plate with uniform wall temperature is more generally taken as 0.59, see for example McAdams [7] and Holman [1].) The replacement of Rayleigh number in vertical plate free convection correlations by an expression of the form $Racos\theta$ was first proposed by Rich [12]. The modification proves to be highly satisfactory where a heated plates faces downward, but not in the upward-facing