New understanding of heat transfer deterioration and its prediction

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Heat transfer deterioration (HTD) may be encountered in forced or mixed convection when the heat transfer effectiveness is significantly lower than expected based on the Reynolds number of the flow. Such phenomena have recently become a new focus of investigations in pursuit of designing new efficient thermal systems, which make use of supercritical fluids (in power cycles), or very high heat flux conditions (in electronics, space, and nuclear fusion systems), or uncommon cooling media, such as liquid metals and molten salts. Under such conditions, strong variations of thermal physical properties of the fluid and non-uniform body forces, such as buoyancy and magnetohydrodynamic forces, may cause flow laminarisation and deterioration of heat transfer. This may not only reduce the efficient of the system but potentially result in safety risks under certain conditions. Despite it being a classical problem, the predictions of HTD remain a challenge in both engineering calculations using correlations and numerical simulations with CFD.

In this talk, we will discuss some new understanding of HTD phenomena recently established with the aid of direct numerical simulation (DNS), which leads to improved predictions of HTD, including the estimations of friction factor and Nusselt number of strongly heated pipe flows, for example. First, we will consider the effect of body forces (such as buoyancy) on turbulence in an isothermal flow. In contrast to the common understanding, we will show that applying such a force does not cause significant changes to key turbulence characteristics (including mixing) based on a new Equal Pressure Gradient reference framework. The so-called flow laminarization can now be explained using a newly-defined Apparent Reynolds Number (ARN). This concept is next applied to strongly heated air flow in a pipe. The ARN is used to produce a Reynolds number/Grashof number map to display the flow laminarisation (severe HTD) and recovery regimes, which agrees well with DNS data. Furthermore, the ARN predicts the presence of a bi-state region where the flow may be turbulent or laminar-like (corresponding to mild or severe HTD). This finding can be used to explain some of the large scatters in experimental Nusselt numbers in the strong HTD region. Thirdly, we analyse a strongly-heated supercritical fluid flow in which severe HTD occurs due to complex reasons. The application of the ARN led to the establishment of a unified explanation for HTD mechanisms due to the variations of thermal properties, flow acceleration due to heating and buoyancy, all of which are treated as pseudo-body forces. The theory also explains the effect of spatial flow development on turbulence using pseudo-body forces. Finally, we demonstrate how the ARN can be used to predict friction factor and Nusselt number as well as turbulent shear stresses and temperature profiles in laminarised and HTD flows.