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FLUID PROPERTY VARIATIONS IN MICRO-CONVECTION

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ABSTRACT

Micro-convection characteristics differ from those in the conventionally-sized channels; these deviations are attributed to microscale effects. Studies revealed the need for better demarcation of the continuum and free-molecular flow regimes, which necessitates the identification of non-rarefaction effects [1]. An important non-rarefaction effect is the role of variations in fluid properties [viscosity (μ), thermal conductivity (k), and density (ρ)]. The effects of property variations with fluid temperature (T) become significant from macro-to-microscale. Further, these effects along the flow direction (z) become more significant relative to over the cross-section (r); which necessitates consideration of additional mechanisms at the microscale, in addition to mechanisms known for the macroscale [2]. The comprehensive pure continuum-based conservation equations for 2-D laminar flow with axisymmetry were theoretically examined and numerically solved for micro-tube of radius, R.

Single-Phase Liquid Micro-Convection with $\mu(T)$ and $k(T)$: The $\mu(T)$ distorts the axial velocity $u(r,z)$-profile and varies this distortion along z, which induces radial flow (v) by flow continuity. The induced radial convection can be a significant percentage of axial convection, i.e. $\left[\int_0^R v\cdot(\partial T/\partial r)\cdot r\cdot \mathrm{d}r\right] \Big/ \left[\int_0^R u\cdot(\partial T/\partial z)\cdot r\cdot \mathrm{d}r\right] \to \mathrm{O}(1)$. Also, axial conduction is induced due to k-variation along z for the constant wall heat flux (q''_w) boundary condition, given as, $\partial/\partial z[k\cdot(\partial T/\partial z)] = (\partial k/\partial z)\cdot(\partial T/\partial z)$. It's non-dimensionalisation by (q''_w/D), indicates heightened significance for large q''_w at the microscale; i.e. $(\partial k/\partial z)\cdot(\partial T/\partial z) \propto D^{-2}$, as q''_w (permissible) $\propto D^{-1}$ [2]. The effect of distorted $u(r,z)$-profile and induced $v(r,z)$-profile on micro-convection [Nusselt number (Nu) value] are opposite, but k-variation along and across z have the same effect. Thus, deviation in Nu due to $k(T)$-variation can exceed the deviation due to $\mu(T)$-variation, though dimensionless μ-T sensitivity is higher than k-T sensitivity [3].

Gas Micro-Convection: Steep $\rho(r,z)$-gradients for the case of air-heated result in flattening of $u(r,z)$-profile, and the rate of flattening is non-negligible. This high rate of flattening can result in hydrodynamic undevelopment of flow, which is the reverse process of flow-development [4]. The Nu is degraded by the induced radially outward

$v(r,z)$ and radial convection, and by the low ρ in the vicinity of the wall [5]. Even at very low Mach numbers, $\rho(r,z)$-variation is induced by ρ-T sensitivity. Consideration of $\rho(r,z)$-variation with pressure (p) and T, together with $\mu(T)$ and $k(T)$, enabled capturing of physical effects as summarised in Table 1 [6].

Table 1. Role of $\rho(p,T)$, $\mu(T)$, and $k(T)$ variations of air on micro-convection [6].

(a) Indirect effect on Nu {through velocity profiles [$u(r,z)$, $v(r,z)$]}

Case	$\rho(r,z) \rightarrow u(r,z)$	$\rho(r,z) \rightarrow v(r,z)$	$\mu(r,z) \rightarrow u(r,z)$	$\mu(r,z) \rightarrow v(r,z)$
$q''_w > 0$ (air-heated)	$u(r)$ flattens along z: $Nu\uparrow$	$v>0$ (radially outward): $Nu\downarrow$	$u(r)$ sharpens along z: $Nu\downarrow$	$v<0$: $Nu\uparrow$
$q''_w < 0$ (air-cooled)	$u(r)$ sharpens along z: $Nu\downarrow$	$v<0$ (radially inward): $Nu\uparrow$	$u(r)$ flattens along z: $Nu\uparrow$	$v>0$: $Nu\downarrow$

(b) Direct effect on Nu

Case	$\rho(r)$-profile	$k(r)$-profile	$k(z)$-variation
$q''_w > 0$	Inverted-'U'-shaped: $Nu\downarrow$	'U'-shaped: $Nu\uparrow$	increasing along z: $Nu\uparrow$
$q''_w < 0$	'U'-shaped: $Nu\uparrow$	Inverted-'U'-shaped: $Nu\downarrow$	decreasing along z: $Nu\downarrow$

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