ABSTRACT

Thermoviscous expansion of a fluid along a periodically heated wall constitutes a novel and intriguing thermo-mechanical pumping method that is capable of inducing net fluidic transport along the wall. Thermal diffusion, temperature-dependent density and viscosity variations, interplay among multiple length scales - all these factors play incredibly critical roles in this transport. In the present dissertation, four problems have been studied, starting from flow over a flat plate (an unconfined flow configuration). Each of second and third problems adds a new length scale to the flow phenomena, thereby, making it more challenging to analyze. Finally, the fourth problem focuses on substantiating one of the potential applications of such flow, that is, obtaining dispersion free transport in microchannels.

The first problem delineates the dynamics of spatiotemporally periodic flow over a flat plate originating out of periodic thermoviscous expansion of the fluid, as a consequence of a thermal wave applied on the plate wall. Two appropriate length scales, namely, the wavelength of the temperature wave and the thermal penetration depth, are identified. Based on the length scales and the analytical solution for the temperature field, the flow field is demarcated into three different layers, namely, the wall layer (which is further sub-divided into various sub-layers, based on the temperature field), the intermediate layer, and the outer layer. Scaling analysis reveals that the entire thermal fluctuation and the subsequent thermoviscous forcing remain confined within the wall layer. Precisely, it is the interaction between the pressure oscillation and temperature-dependent viscosity that yields a unidirectional mean or net (time averaged) flow within the wall layer opposite to the direction of motion of the temperature wave. We also obtain an appropriate scale for the fully developed mean flow velocity at 'periodic steady-state' for fluids having Prandtl number close to unity, which we further substantiate by full scale numerical simulations. The friction factor (dimensionless wall shear) is found to vary inversely with a single dimensionless quantity called the 'thermoviscous actuation parameter'. Our results may constitute a new design basis for simultaneous control of the net throughput and mixing over a solid boundary, by the judicious employment of a traveling temperature wave.

When the mean Prandtl number (Pr_0) deviates considerably from unity, an additional length scale (viscous penetration depth) starts influencing the concerned dynamics of instantaneous as well as time averaged flow. Accordingly, in the second problem, the limiting cases of high and low Prandtl numbers ($Pr_0 >> 1$ and $Pr_0 << 1$) are investigated through detailed order of magnitude analysis. Our study reveals that the viscous penetration depth scales universally with Pr_0 so long as such depth remains small compared to the wavelength of the applied thermal wave. The most intriguing result about this study is that while a high Pr_0 is found to obstruct the mean flow, the converse is not necessarily true. Numerical analysis (CFD) clearly shows that a low Pr_0 fluid can induce negative thermoviscous force within the wall layer and thus retard the mean motion, leading to a nontrivial reduction of net throughput along the plate. Numerical prediction of friction factor variation with Pr_0 agrees well with the scaling estimates for both high-Pr_0 ($\overline{\tau}_w \sim \mathrm{Pr}_0^{3/2}$) and low-$Pr_0$ ($\overline{\tau}_w \sim \mathrm{Pr}_0^{1/2}$) fluids. The findings may very well act as fundamental design basis for engineering devices that may potentially be developed on the basis of the underlying physical principle.

The third problem elucidates the dynamics of thermoviscous pumping process triggered by identical temperature waves travelling along the walls of a two-dimensional parallel plate channel. Spatial confinement may impose serious restrictions on thermal expansion of the fluid, altering the velocity field dramatically as compared to the unconfined flow situations. Depending on channel height to thermal penetration depth ratio and channel height to thermal wavelength ratio, such channels are grouped into three categories – ‘thin microchannel’, ‘thick micro-channel’ and ‘thick channel’, each of which is characterized by distinct physical scales for instantaneous as well as time averaged (net) velocities. It is found that the ‘thick microchannel’ flow exhibits a spatially uniform net velocity profile, resembling the plug-like electroosmotic flow with thin Electric-double-layer. Remarkably, this uniform net flow is represented by a ‘universal’ scale that, in turn, depends not only on the fluid properties (heat diffusivity, thermal expansion coefficient, thermal viscosity coefficient and Prandtl number) and wave characteristics (amplitude, wavelength and speed of the thermal wave) but also on the channel height. Results from the present study are expected to provide valuable insights towards arresting hydrodynamic dispersion in microchannels by non-electrochemical means, following a pH-independent route.

Finally, we numerically investigate hydrodynamic dispersion of a non-reacting species in microchannel flow driven by thermoviscous actuation. Based on the differences in spreading behavior of a solute, as obtained from comprehensive CFD simulations, new time regimes (an “oscillating regime” and a “stable regime”) are identified. Our results reveal that the axial dispersion coefficient (D_{eff}) of a species periodically fluctuates till the variance of concentration distribution equals half of the square of thermal wavelength. Such oscillation essentially dies down as the variance grows further, leading to a “stable regime” of dispersion. While the oscillation of axial dispersivity (D_{eff}) is considerable in a ‘thin microchannel’, the same is found to be inconsequential in ‘thick microchannels’ as the temperature field remains uniform throughout the channel core. Moreover, for a given Peclet number, the coefficient (D_{eff}) can be decreased further by reducing the thermal penetration depth compared to the channel height. The ‘thick micro-channels’ are thus capable of arresting the (axial) spreading of an injected solute in the flow direction and naturally aid the separation processes in microfluidic applications.

Keywords: Thermal expansion, Temperature-dependent properties, Travelling temperature wave, Length scales, ‘Periodic steady-state’, Time-averaged velocity, Thermoviscous forcing, Prandtl number, Viscous penetration depth, Friction factor, Thermoviscous actuation parameter, Microchannel, Uniform flow, Axial dispersion coefficient, Scaling analysis, Computational fluid dynamics.