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Experimental investigation of heat transfer enhancement factors in the oscillating flow heat exchanger using Kurzweg's and Nishio's correlations

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ABSTRACT

In the present work, an experimental investigation of heat transfer enhancement parameters of the oscillating flow heat exchanger using Kurzweg's and Nishio's correlations is carried out. An oscillatory axial movement of fluid is established within the flow tube using piston cylinder mechanism. The experiments are carried out for seven different frequencies, five tidal displacements and four heat fluxes. It is observed that at a constant tidal displacement (S), experimental effective thermal conductivity (k_{eff}) increases progressively with frequency (f) up to a maximum and then decreases. The frequency corresponding to peak k_{eff} is an optimum frequency. In addition to this, it is also observed that with increase in S, the point of peak k_{eff} is shifted towards lower frequency. A similar trend is observed for axial heat flux (q_a) and convective heat transfer coefficient (h). Based on the dimensional analysis and experimental data, an empirical correlation is obtained for experimental effective thermal diffusivity (α_{eff}) as a function of the Womersley number (Wo) and the transition number (β). Finally the result shows that, in the oscillating flow heat exchanger, f, S, Prandtl number (Pr) of fluid, fluid thermal properties to wall thermal properties, and the ratio of length of cooling tube in heat sink (L_c) to S are primary influencing parameters.

1. Introduction

Fluid flow and heat transfer in circular tubes, ducts and channels is easy to analyze and well established. However, analysis of heat transfer and fluid flow in oscillating flow is complex in nature due to the presence of more stringent time and spatial resolution present within the cycle. In oscillating flow, the flow condition changes cyclically. This results in near wall velocity overshoot, where maximum velocity no longer occurs at the center of the channel. This velocity profile has a significant influence on the heat transfer characteristics. Researchers have demonstrated that the oscillating flow heat exchanger has potential to transport heat at the rate higher than that in a conventional heat pipe. It is capable of removing heat from a concentrated heat source and spread it over a large area which is far away from the heat source. In oscillating flow heat exchanger, diffusion of heat in axial direction takes place by the combined effect of time dependent transverse conduction coupled with the axial convective heat transfer. However, it is independent of how oscillations are generated. Since the fluid used in this type of heat exchanger is not constrained to the saturation temperature, unlike in case of heat pipe, the flexibility for selection of a working substance for various applications is greatly increased. This type of heat transfer method finds applications in the removal of heat from radioactive fluid without net mass transfer, in processes where, the natural convection process is not present and also in cooling of high heat flux generating electronic gadgets.

Heat transfer phenomena due to oscillating flow are naturally complex and least understood. Significant studies have been reported on heat transfer in oscillating flow in the past by various researchers. Kurzweg and co-workers [1–6] examined enhanced heat conduction through sinusoidal oscillatory flow in a circular tube connecting the two reservoirs which were maintained at different temperatures. They observed that the heat transfer enhancement is proportional to the square of the oscillation amplitude and is a function of tube radius, frequency, Prandtl number and on flow behavior. Compared to molecular conduction the enhanced axial diffusion is significantly higher in magnitude because of the high value of thermal diffusivity. This higher value of thermal diffusivity corresponds to the point at which thermal diffusion time equals to

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Nomenclature

A_c	cross-section area of pipe (m^2)
A_{sc}	pipe outer surface area for cooling region (m^2)
a	half channel width or $d/2$ (m)
C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
d	diameter of flow tube (m)
f	oscillation frequency (Hz)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
k	thermal conductivity (W m^{-1} K^{-1})
k_{cu}	thermal conductivity of copper (W m^{-1} K^{-1})
k_{eff}	experimental effective thermal conductivity (W m^{-1} K^{-1})
k_{effk}	theoretical effective thermal conductivity using Kurzweg's correlation (W m^{-1} K^{-1})
k_{effn}	theoretical effective thermal conductivity using Nishio's correlation (W m^{-1} K^{-1})
L_c	length of cooling tube in tube side of shell and tube heat exchanger (m)
m	mass flow rate of shell side cooling water (kg/s)
Pr	Prandtl number
$P(Wo)$	ratio of enhanced thermal diffusivity to molecular diffusivity normalized in such way that it is function of Wo only
Q	heat rate (W)
Q_{out}	heat output (W)
q_a	axial heat flux (W/cm^2)
Re	Reynolds number
r	tube radius (m)
S	oscillation tidal displacement (m)
T_1–T_{10}	temperature at different test points as shown in Fig. 1(a) (°C or K as stated)
T_c	mean temperature of hot water inlet to heat exchanger (°C or K as stated)
T_h	mean temperature of copper tube near heater (°C or K as stated)
T_{mcs}	mean of inlet and outlet temperature of water on shell side (°C or K as stated)
T_s	mean surface temperature of tube of shell and tube heat exchanger (°C or K as stated)
u	velocity component in radial direction (m/s)
Wo	Womersley number
Δx	distance between heat source and heat sink (m)

Greek symbol

α	thermal diffusivity (m^2/s)
α_{eff}	effective thermal diffusivity (m^2/s)
α_{effk}	theoretical effective thermal diffusivity using Kurzweg's correlation (m^2/s)
α_{effkfw}	theoretical effective thermal diffusivity using Kurzweg's correlation by considering thermo physical properties of fluid and tube wall (m^2/s)
α_{effn}	theoretical effective thermal diffusivity using Nishio's correlation (m^2/s)
α_f	thermal diffusivity of fluid (m^2/s)
α_w	thermal diffusivity of tube wall (m^2/s)
β	transition number
κ	constant
ν	kinematic viscosity (m^2/s)
ρ	density of water (kg/m^3)
σ	ratio of thermal diffusivity of fluid to tube wall (α_f/α_w)
τ	function of σ, ψ, χ and Pr (Eq. (14))
χ	ratio of thermal conductivity of fluid and wall, respectively (k_f/k_w)
ψ	function of Pr $[Pr/(Pr-1)]$
ω	angular frequency of oscillation (rad/s)

Subscripts

Ex	experimental
f	fluid
Th	theoretical
w	wall

half period of oscillation (π/ω) and is represented as $Wo^2Pr = \pi$. Where, Womersley number (Wo) is defined as the ratio of oscillating inertia force to the viscous force. In this condition, there is enough time for heat to flow in either direction between core to wall before the temperature reverses. Heat flow as high as 10^{10} W/m^2 may possibly be reached, provided turbulence and viscous heating does not become a problem at high values of tidal displacement and frequencies needed to get this. They experimentally studied the onset of turbulence in the oscillating flow of water in a small diameter tube. It is observed that as Wo decreases, the value of transition number (β), rises above 2000. It is also found that, with decreasing Wo, flow becomes stable.

Kaviany and co-workers [7–9] mentioned some aspects of enhanced heat diffusion in the fluid by oscillation and analyzed the performance of heat exchanger analytically and experimentally. It is observed that, the best condition for largest thermal diffusion is subjected to physical and mechanical constraints. These constraints include maximum pressure, frequency, channel width, fluid, channel wall thickness and viscous dissipation. Scotti et al. [10] described various heat exchanges where an oscillating flow of primary coolant is used to dissipate an incident heat flux. They observed that at high frequency, very high effective thermal conductivity is obtained which allows the transfer of heat nearly isothermally as in a heat pipe. Nishio et al. [11] presented the effect of physical properties of the working fluid on the heat transfer enhancement in oscillation induced heat transport. They concluded that the fluids with $Pr \approx 1$ are capable of maximizing k_{eff} under optimum condition. With this consideration, water is the best fluid for such system. Angie et al. [12] observed that k_{eff} of oscillating fluid in a pipe is proportional to the product of the square root of the oscillation frequency and oscillation amplitude. Akdag and Feridun [13] proposed correlation for cycle average Nusselt number for oscillating flow in the vertical annular liquid column. Walchli et al. [14] in their investigation demonstrated a numerical modeling approach to predict the performance of a self-contained, reciprocating liquid cooling system for low form factor electronic device. The same numerical model is experimentally demonstrated by a self-contained, reciprocating fluid flow loop.

Mehmet and Mustafa [15] investigated the oscillating flow in porous media of the steel ball. They observed that the local Nusselt number increases by frequencies and displacement, whereas, space average Nusselt number increases by the kinetic Reynolds number and non-dimensional fluid displacement. Patil and Gawali [16,17] studied experimentally heat transfer characteristics of oscillating flow heat exchanger for different frequencies and tidal displacements. Bagci et al. [18] indicated that, in open cell metal foam, friction factor for oscillating flow is higher than that in a steady flow. Wasan et al. [19] developed an experimental apparatus and technique to investigate heat transfer in oscillating flow.