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Heat transfer in a partially filled rotating pipe with single phase flow

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ABSTRACT

Single phase heat transfer in a partially-filled, rotating horizontal pipe with axial liquid (water) flow is studied in this work. Thermal imaging is used to capture outer wall temperature of the partially filled rotating heated pipe. Local heat transfer coefficient along the length of the rotating pipe is calculated. Various parameters influencing the heat transfer coefficient i.e. heat flux (779–12522 W/m^2), flow rate (6–80 LPH) and rotation rate (5–300 RPM) are identified and reported. It is observed that heat transfer is positively influenced by heat flux, flow rate and rotation rate. A generalised correlation is developed based on dimensionless heat flux, flow and rotation Reynolds number to predict the average Nusselt numbers. This study is expected to provide insight into single phase heat transfer characteristics of a partially filled rotating heated pipe.

1. Introduction

Axially rotating channels are widely used in power industries, chemical engineering, aircraft engines etc. The rotation rate about the channel axis is a variable, and is in general, operated at a constant rate in industrial applications. Rotation has a substantial effect on the character of the flow profile and heat transfer.

Flow in a fully filled horizontal rotating pipe with continuous inflow and outflow of fluid is well documented in the literature [1–6]. White [1] investigated the flow of water in a fully filled pipe rotating about its longitudinal axis. Flow resistance is reported to be reduced when Reynolds number corresponding to turbulent flow is introduced in a rotating pipe. At higher rotation rates, pressure loss reduction by approximately 40% is reported. Flow visualization experiments confirmed the reduction in migration of fluid particles from the central core towards the pipe wall in a rotating pipe. Cannon and Kays [2] investigated the effect of pipe rotation on heat transfer in a fully filled pipe rotating about its axis. A stabilizing effect is reported due to the pipe rotation. The flow stabilization due to pipe rotation also influences the heat transfer in the apparatus and a transition towards laminar profile is observed. Murakami and Kikuyama [3] reported that the swirling flow component introduced by the rotating pipe wall decreases the hydraulic losses and hence improves the stability of the flow. Reich and Beer [4,5] studied the effect of pipe rotation using air as the working fluid. Both laminar and turbulent flow is introduced in the pipe to study the effect of pipe rotation on the flow profile and overall heat transfer rate. When laminar flow is introduced into the fully filled rotating pipe, the pipe rotation destabilizes the laminar flow and thereby, generates turbulence. However, when turbulent flow is introduced into the rotating pipe, the turbulence in the flow gets supressed. The pipe rotation supresses the radial turbulent migration of fluid particles as highlighted previously by White [1] and Cannon and Kays [2]. This leads to reduction of flow resistance and heat transfer. Shevchuk and A. A. Khalator [6] reported a detailed review of heat transfer and flow dynamics studies in rotating systems.

Fluid flow profiles inside and outside of a rotating horizontal cylinder with a specific liquid loading is extensively studied and reported in the literature [7–21]. Phillips [7] conducted experimental and numerical studies to describe the oscillations (centrifugal waves) observed on the free surface of the rotating fluid body. Karweit and Corrsin [8] experimentally studied the various flow patterns inside a rotating partially filled horizontal cylinder. Various flow patterns such as pool flow and formation of fluid finger pattern is reported. Moffatt [9] reported experimental studies describing the dynamics of a thin film of viscous fluid on the outer surface of a horizontal rotating roller.

Johnson [10] numerically investigated four different flow profiles i.e. pool flow, two partial coating flow configurations and rimming flow inside a partially filled rotating cylinder. Precise transition film solutions for the above mentioned flow configurations are reported. Melo [11] used lubrication approximations to numerically reconstruct the various fluid flow profiles inside a partially filled horizontal rotating cylinder. Two parameters namely fluid volume and angular velocity were varied to characterize the various stable fluid flow profile domains. Lin and Groll [12] experimentally investigated the stability of

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Nomenclature

A	Area (m^2)
C_p	Heat capacity (J/kg K)
D	Inner diameter of pipe (m)
H	Liquid pool height (m)
h	Heat transfer coefficient (W/m^2K)
k	Thermal conductivity (W/m K)
L	Length (m)
$\dot{Q}$	Volume flow rate (m^3/s)
$\dot{m}$	Mass flow rate (kg/s)
q''	Heat flux (W/m^2)
$\dot{q}$	Heat generation rate (W/m^3)
r_1	Inside tube radius (m)
r_2	Outside tube radius (m)
T	Temperature (°C)
t	Time (s)
v_0	Superficial liquid velocity (m/s)

Subscript

air	Bulk air
b	Bulk water
local	Local
pool	Liquid pool cross sectional area in a stationary pipe (m^2)
surface	Heat transfer surface area of the pipe (m^2)
s,1	Tube inside
s,1	Tube outside
ss	Tube wall
W	Wall
out	Outlet
in	Inlet
$\infty, 1$	Inside bulk
$\infty, 2$	Outside bulk

Greek symbols

μ	Dynamic viscosity (Ns/m^2)
ρ	Density (kg/m^3)
ω	Angular velocity (rad/sec)
ε	Emissivity
ψ	Dimensionless heat flux

Non dimensional numbers

Re_f	Reynolds number $Re_f = \frac{\rho D v_0}{\mu}$
Ro	Rotation number $Ro = \frac{\omega D}{v_0}$
Re_ϕ	Rotation Reynolds number $Re_\phi = \frac{\rho D^2 \omega}{\mu}$
Nu	Nusselt number $Nu = \frac{hD}{k}$
Pr	Prandtl number $Pr = \frac{Cp\,\mu}{k}$
ψ	Dimensionless heat flux $\psi = \frac{q''}{k\,(T_w - T_{in})\,/\,D}$

annular flow in a partially filled rotating horizontal cylinder. A correlation based on Froude number and fluid volume loading parameter is presented to predict the critical point where annular flow profile will collapse.

Thoroddsen and Mahadevan [13] experimentally studied and reported various fluid flow patterns such as pool flow, fluid pendants, smooth and shark tooth flow profiles. A phase diagram for the various flow transitions and instabilities is also presented. Hosoi and Mahadevan [14] numerically investigated the axial instabilities of the free surface front in a partially filled rotating horizontal cylinder. It is reported that inertia plays an important role in the onset of the fluid instabilities. Flow patterns such as pendants and shark tooth profiles as reported by Thoroddsen and Mahadevan [13] were captured using numerical simulation. Baker et al. [15] experimentally investigated the onset of annular flow, annular flow and its subsequent collapse inside a partially filled rotating horizontal cylinder of finite length. A correlation based on rotational Froude number and fluid loading parameter is presented to predict the critical flow transitions.

Wilson et al. [16] reported highly accurate numerical solutions for steady Stokes flow on a cylinder. The inclusion of higher order terms while calculating the asymptotic solutions in the thin film is highly recommended. Ashmore et al. [17] further included the effect of surface tension to compute the fluid film profile in a partially filled rotating cylinder. Various critical limits based on gravitational parameter is reported which highlights the influence of surface tension on the fluid profile.

Chen et al. [18] experimentally studied the uniform rimming flow profile in partially filled rotating horizontal pipes with very small fluid volume fraction. A critical fluid volume fraction is identified for each experimental configuration, where the angular velocity required to achieve uniform rimming flow is minimum. Duffy and Wilson [19] numerically investigated the flow of a fixed fluid mass on a uniformly heated or cooled rotating cylinder with temperature dependent fluid viscosity and large Biot number. It is reported that the solution for fluid velocity, pressure and temperature can be expressed in terms of fluid film thickness. The film thickness can be calculated from the isothermal flow condition where the fluid, wall and the surrounding temperature is equivalent. Chicharro et al. [20] used laser-plane technique to obtain time series data for various flow profiles inside a partially filled rotating horizontal pipe. It is also identified that correlation dimension can be used to characterize rimming flow patterns.

The above mentioned studies were performed in rotating partially filled cylinders where the fluid volume is fixed and the pipe extremities are sealed. Singaram et al. [21] and Chatterjee et al. [22] reported fluid flow transitions in partially filled rotating horizontal pipe with continuous inflow and outflow of liquid. Singaram et al. [21] reported a detailed study of the fluid film flow profile along the length of the rotating pipe using optical interferometry technique. A correlation to determine the annular fluid film thickness along the length of the rotating horizontal pipes is reported.

Kuo et al. [23], Pattenden [24] and Beckman et al. [25] experimentally studied heat transfer between fluids separated by a rotating tube. Kou et al. [23] studied the variation of heat transfer rate in a partially filled rotating pipe with and without inserts. It is reported that the average heat transfer in a partially filled pipe improves similar to a fully filled rotating pipe. The similarity is attributed to the continuous film that covers the surface of the pipe wall due to rotation. This improves the overall heat transfer area. Eventually the final mixing of the thin liquid film on the wall with the liquid pool at the bottom enhances heat transfer. Kou et al. [23] also identified change in flow pattern leading to change in heat transfer rate as the rotation rate is varied. It is indicated that under the investigated experimental domain, effect of free convection is of lesser importance compared to the rotation of the pipe. Kuo et al. [23] experimentally explored heat transfer characteristics in a partially filled horizontal rotating pipe. Flow rate in the range of 12–240 LPH and rotation rates in the range of 10–500 RPM is reported. Kuo et al. [23] performed the experiment in a 0.65 m long pipe with an outer diameter of 76.2 mm and wall thickness of 6.35 mm. The pipe was heated using external heaters and the inner wall temperature is measured using Patton-Feagan method [26].

Pattenden [24] reported exceptionally large overall heat transfer coefficients which are attributed to the flow instability caused by the rotating pipe. The range of experimental flow rate reported is limited to turbulent region. Pattenden [24] concluded that the effect of axial flow