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Impact of inclination on single phase heat transfer in a partially filled rotating pipe

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ABSTRACT

Heat transfer in a partially-filled, rotating inclined pipe with water flowing through it is experimentally investigated. The test section is a 1000 mm long stainless steel pipe with 32.8 mm inner diameter and 1.1 mm wall thickness. The outer wall is painted black to improve its emissivity. The outer wall temperature distribution is captured using a thermal camera. Uniform wall heat flux (1405–10784 W/m^2), water volumetric flow rate (100–830 ml/min), rotation rate (10–300 RPM) and pipe inclination angle (3° and 6°) are varied to study their influence on the heat transfer coefficient. Local heat transfer coefficient along the length of the partially filled rotating test section is reported. While heat transfer coefficient increases with the increase in wall heat flux, liquid volume flow rate and rotation rate, it decreases with increase in inclination angle. A generalised correlation to predict the average Nusselt number is developed in terms of four dimensionless numbers, viz., the flow Reynolds number to capture the effect of the axial fluid flow, rotation Reynolds number to account for the effect of pipe rotation, flow Froude number to take care of the effect of pipe inclination and dimensionless heat flux to incorporate the effect of wall heat flux on the heat transfer coefficient.

1. Introduction

Fluid flow inside a fully filled rotating pipe is well documented in the literature [1–6]. White [1], Cannon and Kays [2] and Murakami and Kikuyama [3] reported that rotation induces a stabilizing effect in a fully filled turbulent pipe flow. Reich and Beer [4] and Reich et al. [5] investigated the effect of pipe rotation on both laminar and turbulent air flow. It is reported that the pipe rotation suppresses the turbulence in the flow. However, rotation destabilises laminar flow in fully filled rotating pipes. A detailed review of heat transfer in rotating systems is reported by Shevchuk and Khalatov [6].

Extensive studies have been reported on various fluid flow profiles inside and outside of rotating horizontal partially filled cylinders [7–19]. The liquid volume inside the partially filled cylinder is generally fixed. The appearance of centrifugal waves on the free surface inside a partially filled rotating pipe is reported by Phillips [7]. Karweit and Corrsin [8] reported the appearance of various flow patterns such as pool flow and fluid fingers inside a partially filled rotating horizontal cylinder. 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] reported precise transition film solutions between different flow configurations namely pool flow, partial coating flow and rimming flow inside a partially filled rotating horizontal cylinder. Melo [11] used lubrication approximation approach to numerically investigate fluid flow profiles inside partially filled rotating cylinders. Lin and Groll [12] reported a correlation to predict the collapse of annular flow inside a partially filled rotating horizontal pipe based on experimental investigations.

Thoroddsen and Mahadevan [13] experimentally investigated various flow profiles inside a partially filled rotating horizontal pipe. A phase diagram based on liquid volume fraction and pipe rotation rate is developed to indicate the appearance of various flow patterns such as pool flow, fluid pendants, smooth tooth and shark tooth inside a partially filled rotating horizontal pipe. Hosoi and Mahadevan [14] reported that inertia plays a pivotal role towards the onset of fluid flow instabilities inside a partially filled rotating horizontal pipe. Baker et al. [15] developed a correlation based on experimental investigation to predict the onset of annular

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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^2 K)
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)
T	temperature (°C)
t	time (s)

Subscript

surface	pipe surface
b	bulk water
W	wall
out	outlet
in	inlet
local	local

Greek Symbols

ε	emissivity
θ	inclination angle (rad)
μ	dynamic viscosity (N s/m^2)
ρ	density (kg/m^3)
ω	angular velocity (rad/s)

Non Dimensional Numbers

Fr	Froude number $\left(Fr = \frac{\dot{Q}^2}{g \sin\theta D^5}\right)$
Re_f	Flow Reynolds number $\left(Re_f = \frac{\dot{Q}\rho}{\mu D}\right)$
Re_ϕ	rotation Reynolds number $\left(Re_\phi = \frac{\rho\omega D^2}{\mu}\right)$
Nu	Nusselt number $\left(Nu = \frac{hD}{k}\right)$
γ	dimensionless heat flux $\left(\gamma = \frac{q'' D^2}{\dot{Q}\rho C_p T_{in}}\right)$

flow, annular flow and the collapse of annular flow inside a partially filled rotating horizontal cylinder.

Ashmore et al. [16] highlighted the critical limits based on gravitational parameter where surface tension influences the fluid flow profile inside a partially filled rotating horizontal cylinder. Chen et al. [17] experimentally investigated the effect of very small fluid volume loading on the rimming flow profile in partially filled rotating horizontal pipes. Based on the experimental parameters investigated, a critical fluid loading parameter is reported when uniform rimming flow profile is realised at minimum angular velocities.

Numerical investigation conducted by Duffy and Wilson [18] concludes that fluid film thickness can be used to express fluid velocity, pressure and temperature inside a uniformly heated or cooled partially filled rotating cylinder. Chicharro et al. [19] used laser-plane technique to capture transient fluid flow profile data inside a partially filled rotating horizontal pipe.

Studies performed on partially filled rotating cylinders with continuous inflow and outflow of liquid has been reported in the literature. Barnea et al. [20] derived a mathematical model to calculate the annular film thickness, liquid holdup and residence time inside a partially filled inclined cylinder with continuous inflow and outflow of liquid. Singaram et al. [21] and Chatterjee et al. [22] performed flow visualisation studies in partially filled rotating pipes with continuous inflow and outflow of liquid. Singaram et al. [21] used optical interferometry technique to study the annular liquid film thickness along the length of a partially filled horizontal rotating pipe with continuous inflow and outflow of liquid. A correlation to estimate the variation in the annular fluid film thickness along the length of the rotating horizontal pipe is reported.

Kuo et al. [23], Pattenden [24], Beckman et al. [25] and Chatterjee et al. [26] experimentally studied the heat transfer characteristics in partially filled rotating pipes as well as fluids separated by a rotating tube. Pattenden [24] reported that the axial flow rate has lower influence on the heat transfer compared to the rotation rate. Beckman et al. [25] reported that conduction heat transfer plays a major role compared to forced convection heat transfer in the experimental domain explored in their study.

Kuo et al. [23] experimentally studied the heat transfer characteristics in a partially filled horizontal rotating pipe. It is reported that the variation in the flow pattern as a result of pipe rotation leads to the enhancement in heat transfer. Heat is supplied using external heaters where the inner wall temperature is measured using thermocouples [27]. The experiment is conducted on a 0.65 m long horizontal rotating pipe with 76.2 mm outer diameter. Chatterjee et al. [26] conducted single phase heat transfer experimental studies on a partially filled horizontal rotating heated pipe. It is concluded that parameters such as fluid flow rate, rotation rate and wall heat flux positively influence the heat transfer characteristics of a partially filled horizontal rotating heated pipe.

Kascheev and Podymova [28] and Petitjean et al. [29] explored the industrial usability of a rotating inclined pipe with 3° inclination angle for waste processing operations. Kascheev and Podymova [28] derived a mathematical model to estimate the output product temperature, residence time and length of the heating zones of a partially filled rotating calciner. The rotation rate is maintained at 3 RPM with liquid volume flow rates of 10–25 liters per hour (LPH).

The influence of flow transition on heat transfer in a partially filled rotating heated pipe and its application as a rotary evaporator for nuclear liquid waste management is a motivating prospect. Open literature indicates that rotary evaporator for nuclear liquid waste management employs a small inclination angle in its design [28,29]. However, the effect of inclination on the local variation in temperature and heat transfer coefficient in a partially filled rotating heated pipe has not yet been reported in the literature to the best of the authors' knowledge. The current study is focused on providing sufficient experimental data for the design of a partially filled rotary evaporator for nuclear liquid waste management applications. The present study focuses on the following aspects:

- Variation in liquid pool height in an inclined partially filled stationary pipe.
- Effect of pipe inclination on the variation of local temperature and heat transfer coefficient.
- Influence of the angle of inclination in combination with various input parameters i.e., wall heat flux, flow rate and rotation rate, on the heat transfer coefficient.
- Correlation to predict average Nusselt number in an inclined partially filled rotating heated pipe.

2. Experimental setup and procedure

The experimental setup is comprised of a stainless steel pipe with 35 mm outer diameter and wall thickness of 1.1 mm. The test