Flow transition in continuous flow in a partially filled rotating circular duct

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ABSTRACT

Fluid flows in partially-filled stationary and rotating circular duct are encountered in several industrial applications. Liquid pool height plays an important role in the flow patterns and flow transitions in such flows. The present work describes flow transitions from pool flow to annular in an axially rotating, partially-filled circular duct with variable inclination and continuous in flow and out flow. Experimental results reported are obtained by varying the angular velocity between 0-1200 rpm and the inclination angle between 0˚-5˚ using a circular Plexiglas duct of inner diameter 54 mm and length 1000 mm.

KEYWORDS

Flow transition, rotating circular duct, continuous flow.

1 INTRODUCTION

Engineering processes involving continuous flow are constantly evolving in order to achieve better heat transfer, mass transfer and mixing rates. Formation of liquid thin film on the surface of a partially filled rotating cylinder is one way of achieving a higher heat transfer area. Flow in a partially filled non-rotating circular duct is extensively reported in the literature.

Partially filled flow in a circular duct is commonly encountered in multi-phase systems with gas-liquid flow. The main focus in multiphase flow is to understand the influence of gas and liquid flow on the flow profile transitions from stratified to annular and its corresponding effect on the entire process operation. Many researchers working in the field of multiphase flow and heat transfer have investigated the problem of estimating the height of the liquid pool in a partially filled circular duct with flowing liquid. The knowledge of pool height inside a partially filled circular duct under various inclination angles will be helpful to the designer.

Liquid in a partially filled rotating duct is also classified to be a multiphase system; however the flow transition effectively occurs due to the azimuthal rotation of the circular duct. Rotating systems find their application in areas of roller coating industry (photographic films, aluminium foils), paper industries (the Fourdrinier machine), liquid degassers, liquid cooling of turbine shafts, rotating evaporators, dryers and rotating heat circular ducts

Adiabatic multiphase (air-water) flow inside stationary inclined circular ducts is reported extensively in the literature. Many researchers have worked on experimental and analytical study of the stationary pool profile, flow transition and the height of the liquid pool [1-3].Adiabatic single phase annular flow in a partially filled horizontally rotating cylinder is extensively studied in the literature. A partially filled circular duct is rotated about its azimuthal axis to establish a coating flow on its inner walls. However, most of the work is limited to batch systems where there is no inflow and outflow of the liquids [3-10].

Continuous flow inside a rotating cylinder is experimentally studied by Cowen *et al*. [5] and Singaram *et al.* [11]. Rimming flow can be established in a partially filled rotating circular duct with continuous feed and recovery of liquid referred to as ‘continuous mode’ in Singaram *et al*. [11]. The focus of their study is on continuous mode annular flow in a horizontally rotating cylinder to experimentally measure the liquid film thickness in the annular flow regime. They developed a theoretical model to predict liquid film thickness in the annular regime along the length of the duct. Available literature can be categorized based on whether the system is rotating or non-rotating. Rotating systems can be classified further as non-flowing (Batch) and flowing (Continuous) systems.

Fluid flow patterns inside partially filled stationary and rotating circular ducts are of high industrial interest. The knowledge of the liquid flow profile inside a partially filled stationary or rotating circular duct provide with an insight to perform calculations to predict various transport phenomena (heat and mass) and the overall efficiency of the unit operation. Liquid flow profile inside a partially filled rotating cylinder can be broadly classified into four regimes as shown in Fig. 1(a-d).

The hydrodynamic regimes differ from each other based on the aspect ratio of the cylinder, choice of liquid, fill fraction and the rotation speed. For a stationary cylinder, the liquid resides at the bottom as a pool as shown in Fig 1(a) which is commonly termed as pool flow. At very slow rotation rates, a part of the filled liquid remains near the bottom of the cylinder and a thin film arises out of the pool at the bottom and wets the entire inner surface of the cylinder. The fluid film coalesces with the bottom pool on the receding side of the cylinder and generates a ‘bump’ or a ‘flat front’. The bump is parallel to the principal axis of the cylinder and the steep part resembles a flat front as shown in Fig 1 (b) and Fig.1 (c). An accompanying recirculation region is also formed in the pool which grows in the azimuthal direction. At higher rotation rates, a number of different inertial instabilities occur. The thin liquid film pulled out of the pool, thickens. The flat front mode eventually becomes unstable leading to sloshing motion on the rising side of the cylinder. At still higher rotation rates, the sloshing flow becomes axially unstable and changes to a homogenous annular film state wherein all the liquid at the bottom is dragged up the rotating wall to form a nearly uniform annular liquid film. Figure 1 shows the two prominent flow modes in rimming flow – flat front mode (c) and homogenous annular film state (d) [11].

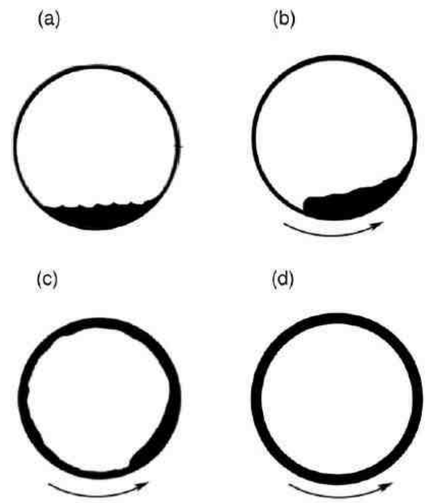


Figure 1(a-d) - Fluid flow patterns inside partially filled stationary and rotating circular ducts [11]

The current study provides an insight into the critical flow transitions in a partially filled rotating system with continuous in and out flow. The results may be useful in studying the influence of flow profile transitions on the heat transfer characteristics inside partially filled rotating heated system. The objectives of the present study are as follows:

- To measure the height of the pool in a stationary horizontal or inclined circular duct and compare with the existing correlations
- To study the fluid flow pattern transitions in an axially rotating circular duct with continuous fluid in and out flow
- To study the effect of inclination on the fluid flow transitions

2 DESCRIPTION OF THE EXPERIMENTAL SETUP

The experimental set up (Fig. 2) consists of a 1 meter long, 60 mm OD, 54 mm ID Plexiglas circular duct attached to a rotor seal on one side and an electric motor on the other side. The liquid flow is introduced into the system using the rotor seal. The liquid exits the circular duct at the other end via an opening between the coupling connecting the motor drive and the circular duct outlet. The DC motor speed is controlled using a VFD controller. The rotation speed can be adjusted between 0-1200 rpm. The rpm measurements are done using both a Lucas make ATH-4R manual tachometer with and accuracy of 0.5% of full scale deflection and a Selec make RC2100 digital tachometer with and accuracy of 0.05%. The whole experimental setup is mounted on a table which can be inclined at a desired angle between 1-5° using a screw jack assembly. The inclination angle is checked based on the elevation change of the raised side using a vernier scale with a least count of 0.02 mm. The flow is supplied from a constant head tank and the flow rate can be varied between 10-60 LPH ± 0.06 LPH using a flow regulator. Liquid hold up in the stationary circular duct at various inlet flow rate and inclination angle is experimentally investigated using catch and hold technique with a measuring cylinder with least count of 1 ml at STP. The liquid holds up values are used to derive the average height, h of the liquid pool in the circular duct.

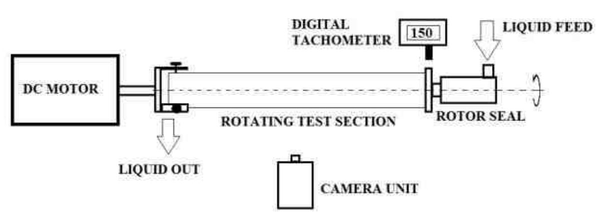


Figure 2 - schematic diagram of experimental setup

Flow profile transition is observed visually using a digital SLR camera; Canon 550D. The inclination of the circular duct is fixed, and for a fixed flow rate the rotation rate of the duct is varied. The flow profile transition along with the appearance and the disappearance of other flow patterns is observed.

3. DATA REDUCTION

The experimental results obtained for a horizontal and inclined rotating circular duct at various flow rates and rotation speeds are classified based on a set of non-dimensional numbers.

Flow Reynolds number, which is the ratio of inertia for force in the axial direction to the viscous force, can be defined for the present problem as given in Eqn. (1)

$$Re_f = \frac{\dot{Q}}{\nu \pi D} \quad (1)$$

where, $\dot{Q}$ is the inlet flow rate (m^3/s) , ν is the kinematic viscosity (m^2/s)

Rotation Reynolds number is defined as the ratio of rotational inertia forces to the viscous

$$Re_\omega = \frac{D^2 \omega}{\nu} \quad (2)$$

where, D is the circular duct inner diameter (m), ω is the angular velocity (rad/sec).

4. RESULTS AND DISCUSSION

The variation of liquid pool height in a partially filled horizontal or inclined circular duct with continuous in and out flow of liquid is investigated. The variation of flow regime in a partially filled rotating circular duct is visually observed. The effect of inclination on the flow regime is experimentally investigated. A correlation is derived to predict the critical rotation Reynolds number at which the fluid flow regime transition will occur.

4.1 Stationary Circular Duct

The height of the liquid pool in a partially filled circular duct is experimentally investigated. The liquid hold up for a constant flow rate and specific inclination inside the partially filled stationary circular duct is measured. The effect of inclination angle on the average liquid pool height inside a stationary circular duct is shown in Fig. 3. The experimental data is tabulated in Table 1.

Table 1 Experimental Pool Height

Flow rate (LPH)	Inclination angle 0°	0.8°	2°	3°	4°	5°
	Pool Height (mm)					
5.49	2.09	1.88	1.27	1.02	0.88	0.72
12.9	2.66	2.13	1.28	1.15	1.08	0.95
24.4	3.34	2.49	1.83	1.62	1.39	1.15
36	3.87	3.24	2.17	1.93	1.73	1.45
48.6	4.36	3.47	2.54	2.13	1.88	1.78
60	4.75	4.19	3.28	2.40	2.58	2.31

The average pool height increases as the flow rate increases due to the increase in the hold up. With the increase in inclination angle (0˚-5˚), the hold-up inside the duct reduces compared to the lower inclinations for a given flow rate. The increase in inclination angle increases the axial gravitational component on the fluid element which leads to an increase in axial velocity of the flow. Increased flow velocity reduces the liquid residence time inside the duct. Hence, a lower hold up is observed. Lower hold up leads to a lower mean liquid pool height.

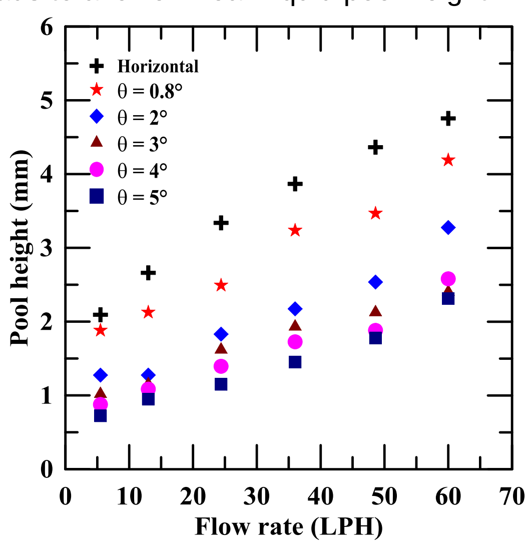
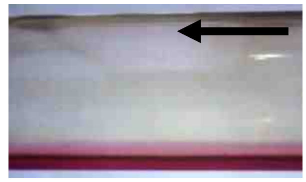


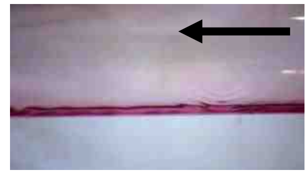
Figure 3 - variation of average pool height with inclination of the duct

4.2 Rotating Duct

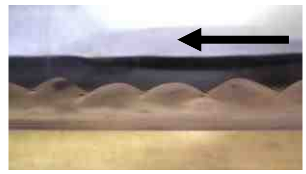
Experiments are performed to visually study the fluid flow profile transition in an axially rotating circular duct with continuous fluid flow. Literature data is available for flow visualisation experiments in batch systems [9, 14]. However, all the data reported in the literature are reported for horizontal systems and the effect of inclination on the flow transition is reported by Chatterjee *et al.* [15].



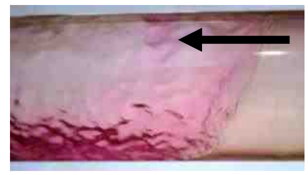
(A) Pool flow
0 RPM



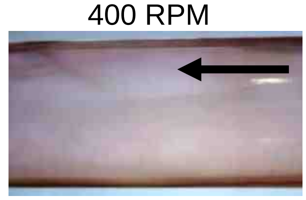
(B)Fluid pendants
60-111 RPM



(C) Smooth tooth profile
400 RPM



(D) Transition to annular profile
500 RPM



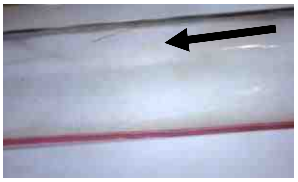
(E)Annular flow
510 RPM

(F)Collapse of annular flow
375 RPM

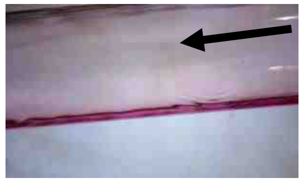
Figure 4 - Fluid flow pattern transition Flow rate: 200ml/min [15]

The different flow patterns identified in the horizontal rotating duct experiment with reference to the reported literature [9, 14, 15] is shown in Fig. 4 (A-F). Fig.4 (A) shows the pool flow profile in a stationary circular duct. At low rotation rates (of the order of 50-100 RPM), flow instabilities termed as “pendents” by Thoroddsen and Mahadevan [9] are observed as shown in Fig. 4 (B). As the rotation rate is further increased, smooth tooth flow pattern is observed as shown in Fig. 4 (C).

Increasing the rotation rate leads to the transition of the fluid flow pattern into annular flow as shown in Fig. 4 (D) and Fig. 4 (E). Gradually reducing the rotation rate leads to the collapse of the annular flow as shown in Fig. 4 (F). Similar flow patterns is observed in partially filled, rotating, inclined as shown in Fig. 5 (A-G).

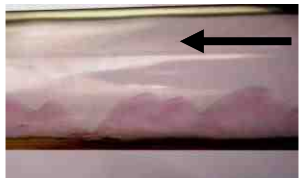


(A) Pool flow
0 RPM



(b) Fluid pendants
57-136 RPM

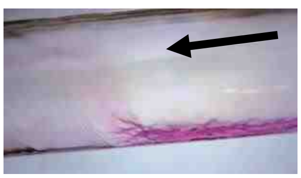
(c) Smooth tooth profile
180 RPM



(D) Shark tooth profile
370 RPM

(E) Transition to annular profile
383 RPM

(F) Annular flow
390 RPM



(G)Collapse of annular flow
346 RPM

Figure 5 - Fluid flow pattern transition Flow rate: 200ml/min, 3˚ Inclination [15]

4.2.1 EFFECT OF INCLINATION ON THE TRANSITION OF FLUID FLOW PATTERNS: The reported flow patterns are observed in all the experimental runs and for all the inclination angles and flow rates explored. However, with the variation of inclination, the pattern transition range varied. The widely reported hysteresis phenomenon between the transition to annular flow pattern with increasing rotation rate and the collapse of annular flow pattern as the rotation rate is decreased gradually is also observed as shown in the Fig.6 (A-F).

The transition of flow pattern from pool flow (L3 curve) Fig. 6 (A-F) to annular flow as the rotation rate is increased as shown by the L2 curve in Fig. 6 (A-F) and the subsequent collapse of annular flow shown by L1 curve in Fig. 6 (A-F) as the rotation rate is slowly reduced in the horizontal rotating circular duct highlights the hysteresis phenomena observed in the performed experiments.

As the duct inclination is increased the range of rotation rate at which the fluid flow profile transition occurred decreases as can be seen in Fig. 6 (A-F). The reduction in the rotation force required to initiate flow profile transition is due to the reduction of the liquid hold up inside the duct as the inclination angle is increased.

It is observed that in the horizontal experiments, the collapse of the annular flow occurred at a much lower rotation rate (above 375 RPM) compared to the rotation rate where the annular flow profile is established (above 500 RPM). However, in the inclined experiments, the collapse of annular flow is observed within 40 RPM of where the transition to annular flow is observed. This variation is due to the amount of fluid holdup in the horizontal circular duct being greater than the hold up in the inclined ducts. The greater liquid holdup amount leads to greater liquid inertia in the rotating circular duct, which leads to a lower rotation rate where the annular flow collapses

4.2.2 CORRELATIONS TO PREDICT ANNULAR FLOW AND THE COLLAPSE OF ANNULAR FLOW: A correlation is developed to predict the critical rotation Reynolds number $Re_{\omega_{critical}}$ when the fluid flow profile inside the rotating horizontal or inclined duct would transition into complete annular profile and collapse from annular flow profile based on the dimensionless pool height in a stationary circular duct (h/D) and the flow Reynolds number Re_f as given by Eqn. 3. The correlation coefficients associated with the onset of annular flow are given in Table 2.

$$Re_{\omega_{critical}} = C_1 {Re_f}^{C_2} (h/D)^{C_3} \quad (3)$$

Table 2 Correlation coefficients for Eqn. 3

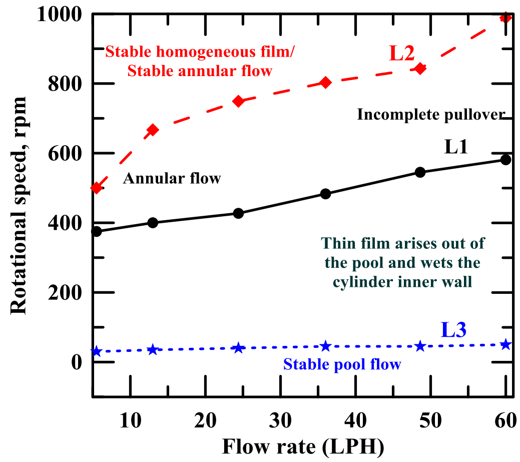
Flow Profile	C_1	C_2	C_3
Annular Flow	1024998	-0.0021	0.5024
Collapse of Annular Flow	164012	0.1247	0.1469

The same correlation, Eqn. 3 can be used to predict the critical rotation number for the collapse of annular flow using the corresponding coefficients for the collapse of annular flow from Table 2. The above correlation agrees reasonably well with the experimental results with a maximum deviation of 20%.

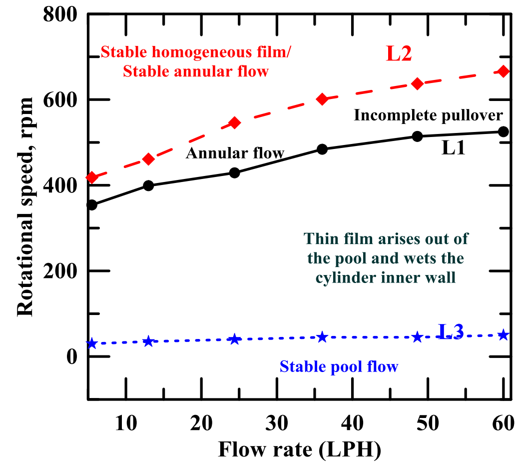
5. CONCLUSIONS

Experiments are performed to study the variation of liquid pool height in stationary horizontal and inclined circular ducts for different flow rates. The effect of inclination (0˚-5˚) on the pool height in a stationary duct is studied. The effect of inclination on the flow pattern and transition in an axially rotating duct is investigated experimentally. The experiments are performed using a 54 mm inner diameter circular Plexiglas duct. The following conclusions are drawn from the present study

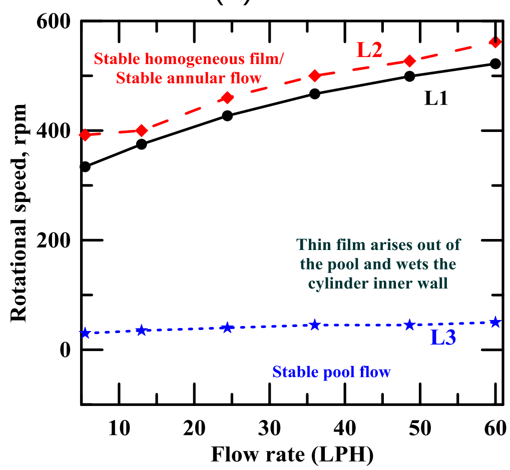
- The flow transition in a partially filled rotating duct is strongly influenced by the angle of inclination.
- Widely reported hysteresis phenomena between annular flow profile and its collapse is reported for inclined continuously flowing rotating circular duct
- A correlation is developed using the stationary dimensionless pool height and flow Reynolds number which can predict the critical rotation Reynolds number for transition into complete annular flow and its collapse.



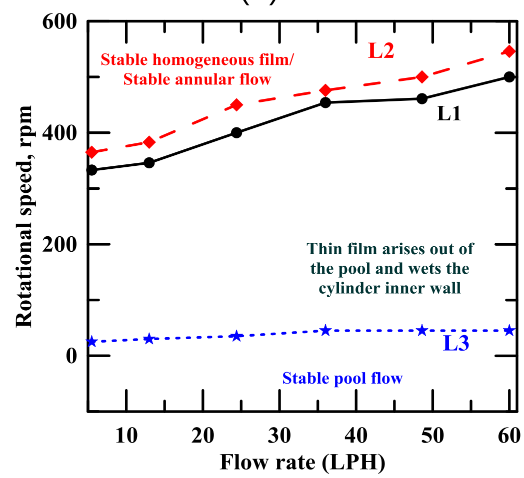
(A) Horizontal



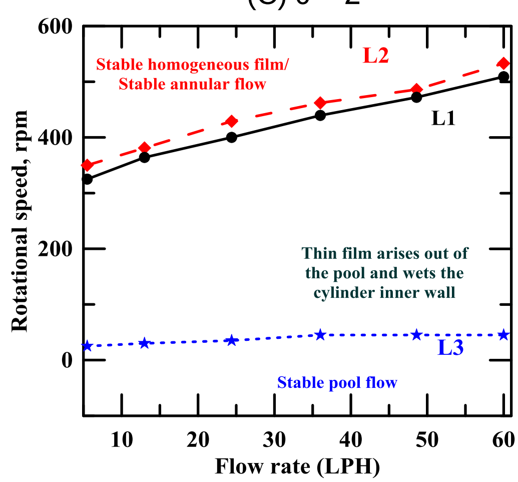
(B) θ = 0.8º



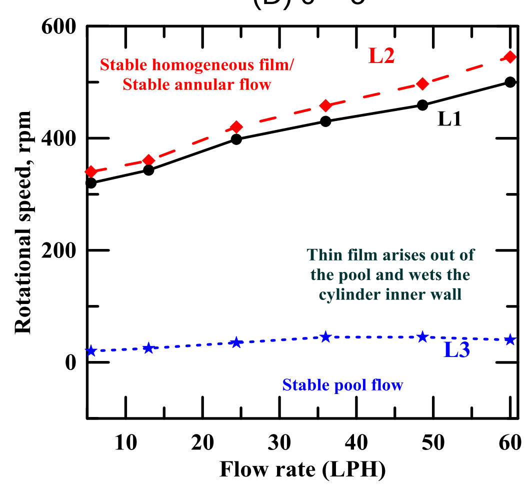
(C) θ = 2º



(D) θ = 3º



(E) θ = 4º



(F) θ = 5º

Figure 6 - Fluid flow profile transition in a rotating circular duct for different inclinations

NOMENCLATURE

h	Liquid pool height (m)
R	Duct inner radius (m)
D	Duct inner Diameter (m)
$\dot{Q}$	Flow rate (m^3/s)
θ	Inclination angle (Degrees)
μ	Dynamic viscosity (Pa s)
v	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
ω	Angular velocity (rad/sec)
Re_f	Reynolds number in terms of diameter of the duct
Re_ω	Rotation Reynolds number

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