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Experimental Studies of Flow Patterns of Different Fluids in a Partially Filled Rotating Cylinder

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Abstract

An attempt has been made to investigate the various parameters affecting the fluid behaviour, partially filled in a rotating cylinder. When the cylinder is rotating at 'high' speed, a liquid forms a hollow cylinder. Different patterns are observed in the fluids for the rotatioal speeds below a critical speed. This study should give us some insight into molten metal behaviour during centrifugal casting. An extensive experimental investigation is required to obtain an appropriate functional relationship by knowing and understanding some dimensionless parameters. Here the effect of dimensionless parameters ε (which is $2\,g/\omega^2 d$, where g, ω and d denotes gravitational acceleration, container rotation rate and inner diameter of liquid cylinder) and G (number of times the gravity) was studied as variation of rotation speed, viscosity and aspect ratio of the mould.

1. Introduction

Because of the numerous technological processes, the analysis of fluid flow behaviour in rotating cylinder has received considerable experimental attention in recent years. The flow in a rotating partially filled horizontal cylinder has been examined experimentally and theoretically over the last 50 years. The system is typical in that although the extreme states of the fluid flow corresponding to angular velocities from zero to infinity is a complicated issue.

Visual observations of different fluids inside a rotating cylinder indicate the existence of certain critical value of the angular velocity for the formation of liquid cylinder. At values of the angular velocity larger than the critical one, the flow is without separation and below these critical speeds the fluid exhibits instability. When some water containing horizontal cylinder is rotated, initially the side walls of the mould lift the adjacent fluid and leads to the formation of a secondary flow. This secondary flow is known as "Ekmann flow". Simultaneously, threads of water are formed along the length of the cylinder, known as "Marangoni flow". As speed is further increased, water forms a uniform coating inside the surface of the mould and this flow is called as "Couette flow". Further increase in speed lifts more water resulting in the formation of a series of ring patterns known as "Taylor flow".

Moffatt (1997) used kinematic wave theory to study the behaviour of a viscous film coating the exterior of the cylinder. It is not surprising to note that many investigations have been directed at a solution of a particular case and no attempts have been made towards generalization of fluid behaviour. Henry (1969) studied the fluid flow and heat transfer in rotating ducts and gave some basic equation for the same.

Mahadevan (1997) described a number of different phenomena seen in the free flow inside a partially filled rotating cylinder. A lot of work has been carried out by Lopez (2004), Evans (2004), Yogesh (2001) and Gans (1988) to study the behavior of fluids in rotating cylinder. Jaluria (2001) explained the importance of fluid flow in material processing and illustrated the nature of the basic problems, solution strategies and issues involved in this area.

It is clear that detailed experiments must be employed to understand the basic problem, and issues involved in this area. Well planned experiments would help us in understanding the fluid flow in a rotating cylinder. In this paper, a experimental study of the various phenomena that affect the behaviour of the fluids rotating from zero to critical speed are studied.

2. EXPERIMENTAL DETAILS

The experimental apparatus consists of a transparent mould fixed to a flange shown in Fig. 1. The flange is connected through a shaft to a 1HP DC motor, with variable speed from 20rpm to 1000rpm. Five moulds having different aspect ratio (which is the ratio of length to diameter of the mould) are given in Table 1. A mould is then fixed to the flange and rotated gradually. The experiments were carried out for three fluids namely water, glycerin and 140EP oil to get an idea of the behaviour of the metal melt during cooling to solid formation.

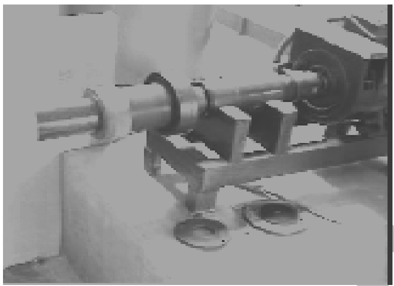


Fig. 1. Experimental Set up

Table 1 Dimension of five moulds

Mould	Mould A	Mould B	Mould C	Mould D	Mould E
Diameter 'D'(cm)	8.1	8.1	8.1	11	11
Length 'L'(cm)	11	14.1	6.5	11	14
Aspect ratio(L/D)	1.35	1.741	0.802	1.0	1.272

The behavior of the fluids at different angular velocities of the cylinder was studied. The volume of liquid required for forming a desired thickness of liquid cylinder is calculated and placed in the cylindrical side. Before rotation, the fluid charged sits in a pool on the cylinder side. The mould is rotated and fluid film is pulled out from the pool and forms a uniform coating inside the surface of the mold known as Couette flow. When the RPM (revolutions per minute) of the mould is increased, at a certain critical speed all the fluid is lifted and forms a hollow liquid cylinder of uniform thickness. The experiements were repeated several times and the results obtained had a variation of about 1%.

Normally one would report results in a dimensionless parameter space. One of the parameters is $\varepsilon = 2\ g/\omega^2 d$, where g, ω and d denotes gravitational acceleration, container rotation rate and inner diameter of liquid cylinder. It is seen that $\varepsilon > 0.162$ is sufficient for instability and $\varepsilon < 0.0847$ is sufficient for stability. Another parameter to describe the spinning speed is in terms of 'G' or the number of gravity force (g) that the mould is running.

3. RESULTS AND CONCLUSION

3.1 Couette flow

Initially, water rests in a pool at the cylinder side. When the mould is rotated, a film is pulled out from the pool and sticks to the inner surface of the mould. It forms a uniform coating on the inside the surface i.e. Couette flow. When a small volume of water, say to form a thickness of 1mm, is used, the water film splits since it does not stick to the entire region of the inner mould and water in form of threads known as Marangoni flow are formed. The Marangoni flow was not seen in case of 2mm or thicker cases since the water covers the entire region of the inner mould.

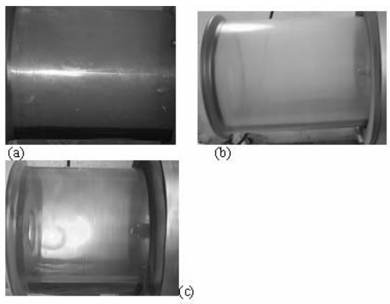


Fig. 2. Couette flow formation of water for E bottle for (a) 1mm thick at 120rpm (b) 3mm thick at 60 rpm; (c) Couette flow formation for D bottle for 3mm thick formed at 100rpm.

After the incidence of Marangoni flow with further increase in speed, the water tries to move in axial direction and simultaneously gets lifted. For thicker water films, the volume of water is enough to cover the entire length of cylinder. The water lifts all along the length during mould rotation and the speed required for the formation of the Couette flow is lowered as seen from Fig. 2.

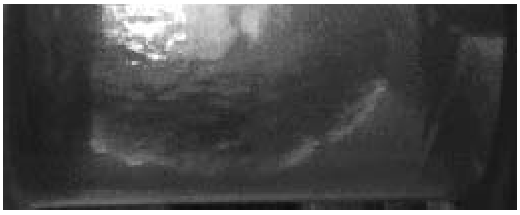
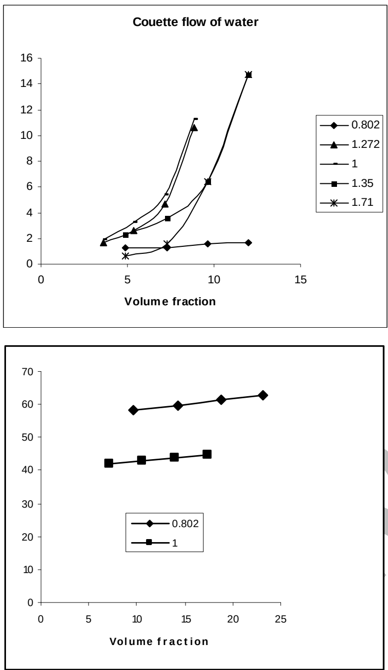


Fig. 3. Ekmann flow disturbing the flow at lower aspect ratio.



(a)

(b)

Fig. 4. The value of ε during the formation of Couette flow for different mould dimensions and volume fraction of fluids (a) water (b) Glycerin and 140 EP oil

Moreover, for small aspect ratio (i.e.0.802) Ekmann flow (end flow) plays a pivotal role in the speed needed in formation of Couette flow. These secondary flows, disturb the lift of the water and hence the formation of Couette flow takes place at higher speeds. Moreover, if the volume of water is increased, the formation of Couette flow takes place at only at increased RPM due to reduced contribution from Ekmann flow Fig. 3. Further for mould D having small length and but similar diameter as mould E, the Couette flow forms at higher rpm with increase in fluid film thicknesses.

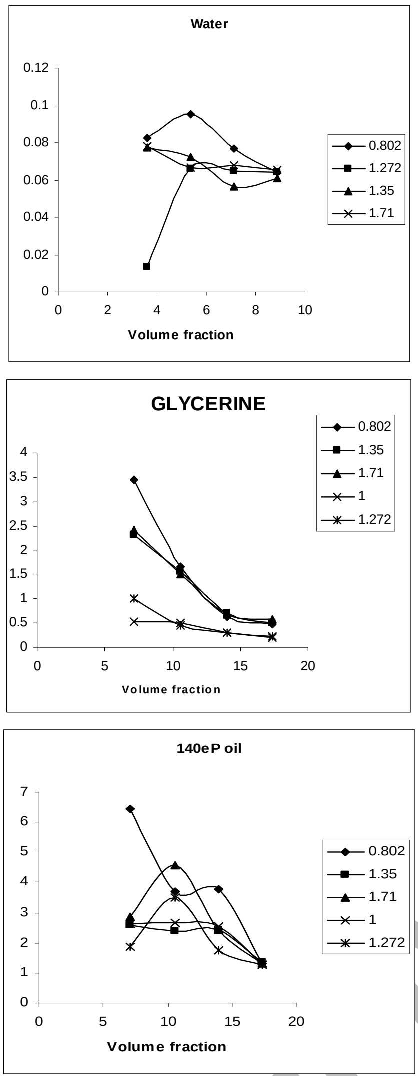
For viscous fluids like glycerin and 140 EP oil the Couette flow formation for all moulds takes place at 20 RPM.

Viscosity seems to play a major role in the formation of Couette flow. For a liquid, the thickness (volume) of fluid taken and aspect ratio of the mould are the parameters to be considered for the formation of Couette flow. The rotational speed is inversly proportional to ε. Hence from Fig. 4 the value of ε is small for larger aspect ratio and larger volume fraction. With smaller volume fraction, the liquid has to move axially and then get lifted. Hence, larger drive is required for the formation of Couette flow. From Fig. 4,a as explained earlier, for aspect ratio 0.802, the value of ε is low due to the supporting effect of Ekmann flow and for larger aspect ratio the formation of Couette flow occurs at higher speeds. From Fig. 4,b, ε varies linearly with volume fraction for the viscous fluids as they easily stick to the inner surface of the mould.

3.2 Formation of complete cylinder

When a mould containing liquid is rotated, a hollow liquid cylinder of uniform thickness forms at a critical RPM. Here a large centrifugal force dominates over gravity leading to the formation of a liquid cylinder. The ε for the formation of liquid cylinders is plotted in Fig. 4. It is seen that for low viscosity liquids like water, the formation of liquid cylinder occurs at higher rpms. As viscosity of fluid increases, the liquid cylinders form at lower rpm. Moreover, for viscous fluids once the Couette flow is formed, then the formation of liquid cylinder takes place for a small increase in the speed.

As seen from Fig. 5 the values of ε converged as the volume fraction of liquid increased. This implies that the rotation speed converges to a common value after certain volume fraction. For high viscosity liquid, 140EP oil at low volume fraction the fluid does not extend uniformly in the axial direction to be lifted to form a coating cylinder. Hence it requires larger G force for the formation of full cylinder compared to large volume fraction cases. As explained earlier the value of G forces tends to converge after certain volume fraction in case of water Fig. 6,a. For high viscosity liquids the value of G converges for an aspect ratio (at same diameter but varying length) as shown in Fig. 6,b,c, which may be the effect of viscosity.



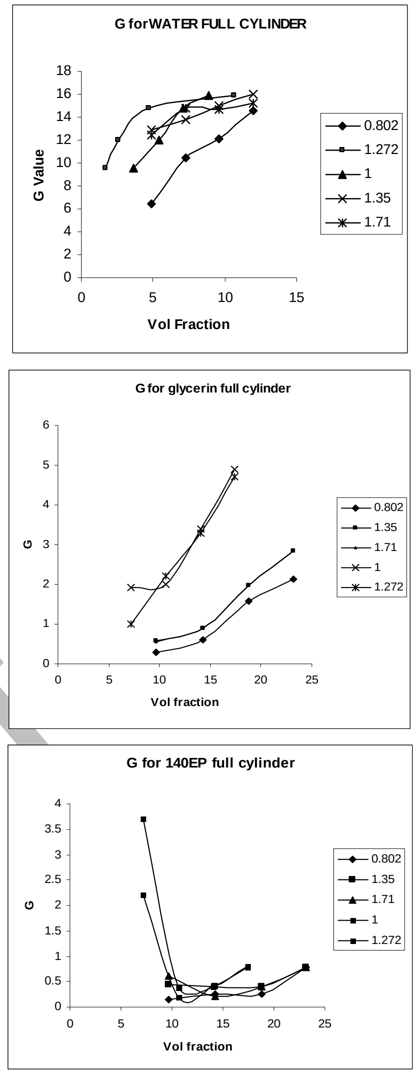
(a)

(b)

(c)

Fig. 5. The value of ε during full formation of liquid cylinder for (a) water (b) Glycerin (c) 140EP oil

As mould speed is increased, all the subsequent layers try to move in the circumferential direction of the mould. Since the water is having low viscosity, these layers will slip during rotation and we observe the water in turbulent stage. When the rpm is increased to a certain value all the layer gets lifted and adheres in their position, thus forming a full cylinder. With high volume fraction, water starts to lift since there is no movement axially. Hence at a particular speed, it forms a full cylinder. Further increases in volume fraction, the liquid cylinder are formed at same rpm as that for lower volume fraction. Hence the value of G tries to converge with increased volume fraction as seen from Fig. 6.



(a)

(b)

(c)

Fig. 6. The value of G during full formation of liquid cylinder for (a) water (b) Glycerin (c) 140EP oil

With high viscous fluids like glycerin and 140EP oil, the procedure involved in the liquids for the formation of liquid cylinder remains same. Here the layer of viscous fluid moves along larger circulferential area compared to smaller diameter of the mould. Hence larger drive is requied to form a complete cylinder. Hence, the value of G converges for a given dimension of the mould.

With For low volume fraction of liquid, amount of the fluid and mould dimension are the important parameters to be considered for the formation of full cylinder. After a certain liquid cylinder wall thickness, the rotation speed for the formation of full cylinder occurs at nearly the same RPM for a given liquid.

3.3 Cylinder breaking

It is also important to study the reverse process. When the RPM is gradually reduced from the critical or larger speed the full cylinder remains intact to a certain reduced RPM after which the liquid cylinder breaks up and the all the fluid drops to the lower surface of the mould. This value of G is calculated for all the fluids for different volume fractions and plotted in Fig. 7. It is seen that the value of G remains in

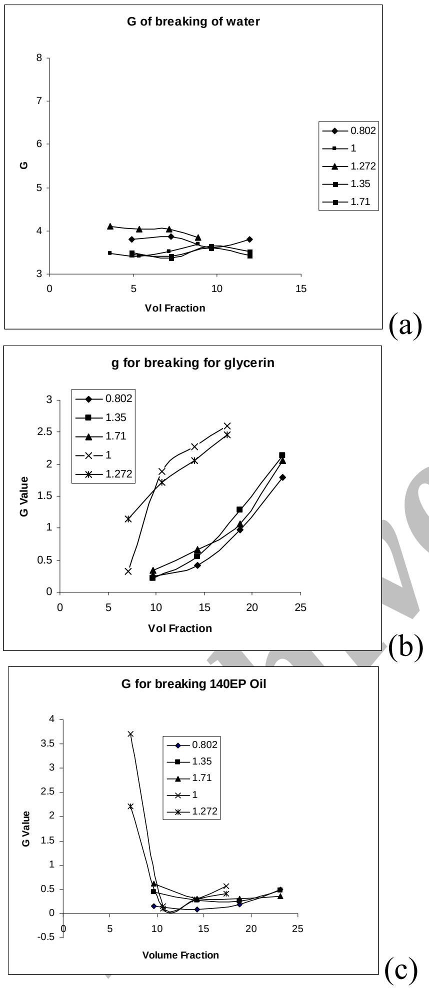


Fig. 7. The value of G during breaking of liquid cylinder for (a) water (b) Glycerin (c) 140EP oil

the range of 3 to 4 for water, 0.25 to 2.5 for Glycerin and 0.1 to 0.6 for 140EP oil. The investigation is confined to a small variation in volume fraction and hence the natures of variation are not clearly spelt out.

4. Conclusion

Experimental studies were conducted to see the behaviour of three fluids namely; water, glycerin and 140EP oil partially filling a horizontal rotating cylinder. The value of ε and G are calculated and plotted and it is seen that after certain volume fraction rotational speed for full cylinder formation remains the same for a given liquid. The effect of above dimensionless parameters influencing the Couette flow, formation of full cylinder and breakup of the formed liquid cylinder are explained.

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