NON-NEWTONIAN FLUIDS DISCHARGE THROUGH CIRCULAR AND SQUARE ORIFICES FROM A TANK

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Orifices are commonly used to control and measure the discharge of Newtonian fluids from pipes, channels, reservoirs and tanks and are available in different types, shapes and sizes. The accuracy of non-Newtonian fluid flow rate measurements through orifices from tanks is not well understood with little research available on discharge of non-Newtonian fluids from circular orifices and not at all on square orifices. In this work, square and round orifices were used. Circular and square cross-section sharp crested orifices with similar hydraulic radii were fitted at the bottom of the tank. A rectangular tank suspended from a weighbridge fitted with a load cell was used to measure the rate of discharge. A rotary viscometer was used to establish the rheological parameters of the test fluids. Water was used for calibration purpose. Different concentrations of glycerine and model non-Newtonian test fluids were used. From the experimental results, the coefficients of discharge (C_d) and orifice Reynolds numbers for each orifice shape were determined. C_d vs Re relationships for the laminar and turbulent regions for each shape orifice were plotted. The average C_d values for both orifices was found to be 0.62 which is close to the oft-quoted value of 0.61 for Newtonian fluids, and there was no difference in Re in the fully turbulent region. The Re values ranged between 10 and 80 000. There is no effect of orifice shape for non-Newtonian fluids but there is an effect of the fluid viscosity and yield stress. This must be incorporated in the process engineering predictions.

KEY WORDS: orifices, discharge coefficient, Reynolds number, hydraulic diameter, rheology

NOTATION

A_0	Area of orifice (m^2)
d	Diameter (m)
k	Consistency index (Pas^n)
n	Flow behavior index
Q	Discharge (m^3/s)
Re	Reynolds number
Re_{MR}	Metzner and Reed (1955) Reynolds number
v	Orifice velocity (m/s)
ρ	Density (kg/m^3)
μ	Viscosity (Pas)
τ_y	Yield stress (Pa)

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τ	Shear stress (Pa)
$\dot{\gamma}$	Shear rate (s^{-1})

1. INTRODUCTION

Orifices are flow metering devices that are simple and easy to construct. As a result, they are usually used to control, regulate and measure Newtonian fluids discharge (Husain, 2010; McCabe et al. 1993). Currently they are not being used to measure the flow rate of non-Newtonian fluids, specifically from tanks. The only study that is available on the flow rate measurement of non-Newtonian fluids using circular orifices out of tanks was by Dziubinski and Marcinkowski (2006). Joye et al. (2003) and Triantafillopoulos, (1988) stated that it is a challenge to handle a non-Newtonian fluid during gravitational drainage from tanks particularly in laminar flow due to their complex rheological behaviour. The factors which improve the efficiency of flow rate measurement through orifices for non-Newtonian fluids are not well understood. Therefore, it is important to study the effect of shape by measuring the discharge of non-Newtonian fluids using different shaped orifices from a tank.

1.1 LITERATURE

Dziubinski and Marcinkowski (2006) studied the flow of Newtonian fluids and a non-Newtonian fluid (CMC) exhibiting power law behaviour, through different diameter orifices with varying L/d ratios from a tank. They used a generalised Reynolds number (Equation 1) to calculate the Re for Newtonian fluids and Metzner and Reed (1955) Reynolds number (Equation 2) for non-Newtonian fluids.

$$Re = \frac{\rho v d}{\mu} \tag{1}$$

$$Re_{MR} = \frac{v^{2-n} d^n \rho}{k\left((3n+1)/4n\right)^n 8^{n-1}} \tag{2}$$

Dziubinski and Marcinkowski (2006) established an average C_d value of 0.62 and 0.67 for Newtonian and non-Newtonian fluids respectively in turbulent flow. They modelled the discharge coefficient for Newtonian and non-Newtonian fluids separately.

Research on the flow rate measurement of non-Newtonian fluids through circular orifices in pipes was conducted by Chowdhury and Fester (2012), Ntamba Ntamba (2011), Rituraj and Vacca (2018). Chowdhury and Fester (2012) and Ntamba Ntamba (2011), used the Slatter and Lazarus (1993) Reynolds number (Equation 3) for the non-Newtonian fluids used. The fluids that they tested represented power law, Bingham and yield pseudoplastic fluids.

$$Re_2 = \frac{8v^2\rho}{\tau_y + k\left(\frac{8v}{d}\right)^n} \tag{3}$$

According to Wand and Fang (2015), for water, circular orifices produce more stable flow than the square shape orifices. This is because the square jets are prone to wind effects and are unstable at high pressure. They found that circular and square orifice Reynolds numbers are similar at low pressures and differ slightly as the pressure increases because of the difference in the hydraulic diameters. Novák and Koza (2013) noted the difference in the results between the circular and square orifices when measuring the flow rate of gas through orifices with large areas. Orifice flow rate relation is given in Equation 4 (Hicks and Slaton, 2014, Prohaska, 2008).

$$Q = C_d A_0 \sqrt{2gh} \tag{4}$$

The objective of this work is therefore to investigate the effect of the fluid viscous properties and orifice shape on the discharge coefficient for non-Newtonian fluids.

2. METHODOLOGY

Water was used for calibration purpose and to standardise the experimental protocols used in this work. Different concentrations of aqueous glycerine solutions, Carboxymethylcellulose (CMC) aqueous solutions, kaolin and bentonite suspensions were tested. A Physica MCR300 rheometer was used to determine the rheological properties of the fluids. For Newtonian fluids, Equation 5 was used to establish the Newtonian viscosity. The Herschel–Bulkley model (Equation 6) was used for characterising the non-Newtonian fluids (Chhabra and Richardson, 2008).

$$\tau = \mu\dot{\gamma} \tag{5}$$

$$\tau = \tau_y + k\left[-\frac{du}{dy}\right]^n \tag{6}$$

Table 1 shows the rheological parameters of the tested fluids.

Table 1

Rheological parameters of the test fluids

Fluid	Conc.	Density	k	n	τ_y	μ	$\dot{\gamma}$	Temp.
	%	kg/m^3	Pa.s^n		Pa	Pa.s	s^{-1}	°C
Kaolin v/v	20.3	1336	3.98	0.36	39.4	-	541-2318	16
	13.1	1217	0.067	0.72	8.9	-	821-2294	18
CMC w/w	7.55	1043	2.39	0.64	-	-	416-2276	18
	6.58	1037	0.882	0.70	-	-	527-2382	18
	5.21	1029	0.209	0.79	-	-	563-2518	18
	2.81	1016	0.017	0.97	-	-	508-2487	18
	2.40	1014	0.006	1.00	-	-	605-2606	25
Bentonite w/w	7.3	1046	0.021	1.00	30.5	-		21
	6.99	1044	0.014	1.00	15.7	-	653-2606	17
	3.77	1023	0.006	1.00	1.13	-	574-2571	18
Glycerine	100	1258	-	-	-	0.973	212-1870	18
	96	1248	-	-	-	0.304	467-1786	19
	93	1242	-	-	-	0.129	435-1756	17
	65	1179	-	-	-	0.019	515-2406	18

Sharp crested circular and square orifices with hydraulic diameters 8, 12, 16 and 20 mm were fitted at the bottom of the tank. A 400 x 400 x 600 mm rectangular tank, weighing 41.2 kg and constructed with clear Perspex walls was used for the flow tests. The suspended weigh bridge with a load cell was attached to the tank to measure the flow rate of the liquids. The data obtained was the change in voltage with time. The voltage was converted to weight from which the fluid height could be calculated as a function of time. The height was plotted against the time and a second order polynomial was fitted to the data. The trend line equation obtained gave the expression of dh/dt, and its derivative was used to compute the discharge at any time. The C_d values were calculated using Equation 4. Equations 1, and 3 were used to calculate the respective Reynolds numbers. The hydraulic diameter was used in the definition of Re. The relationship between C_d values and Reynolds numbers was determined.

3. RESULTS AND DISCUSSION

The circular and square orifices' calibration results are presented in Figure 1. The average C_d value for circular and square orifices is 0.62. The obtained C_d values are within ±4% error when compared to the average C_d value of 0.62 obtained by Dziubinski and Marcinkowski (2006) through sharp crested circular orifices from tanks. The shape of the orifice does not seem to have any effect on the flow rate of water.

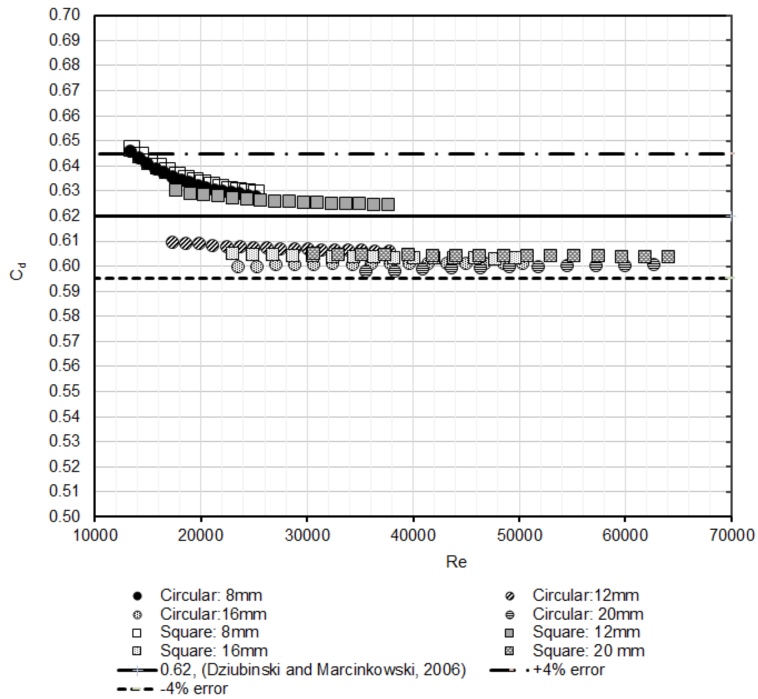

Figure 1. Calibration results for circular and square orifices

Figure 2 shows Newtonian and non-Newtonian flow rate measurement results for circular and square orifices. The Re values range from 10 to 80000 for the two shapes of orifices. There are four flow trends in the laminar region. The highly viscous Newtonian fluids (different concentrations of glycerine) Re values start from Re=10, the power law (CMC) Re values start from Re=50; the yield pseudoplastic fluids (kaolin suspensions) Re values start from Re=250 and Re for Bingham fluids (bentonite suspensions) started from Re=350. A similar trend was observed by Dziubinski and Marcinkowski (2006) as shown by results in Figure 3 for the flow of Newtonian and non-Newtonian fluids through sharp crested circular orifices with L/d of 0. For this work it is assumed that there is a difference in fluid flow trends because of the effect of viscosity and yield stress. Dziubinski and Marcinkowski (2006) C_d values started from Re=0.002 for Newtonian fluids and Re=0.017 for non-Newtonian fluids. They used an orifice size of 5 mm diameter which is smaller than the smallest orifice (8 mm) used in this study.

Considering the effect of orifice shape for highly viscous glycerine and high concentrations of non-Newtonian fluids, the Re values for Newtonian fluids through square orifices are less than Re values through circular orifices in the laminar region. The Re values for CMC solutions, bentonite and kaolin suspensions are similar for square and circular orifices. There is no difference in Re and average C_d values obtained in the turbulent region for Newtonian and non-Newtonian fluids and for square and circular orifices. However, Dziubinski and Marcinkowski (2006) found the average C_d value of 0.67 for non-Newtonian fluids and this might be because of the effect of L/d ratio of the orifices used.

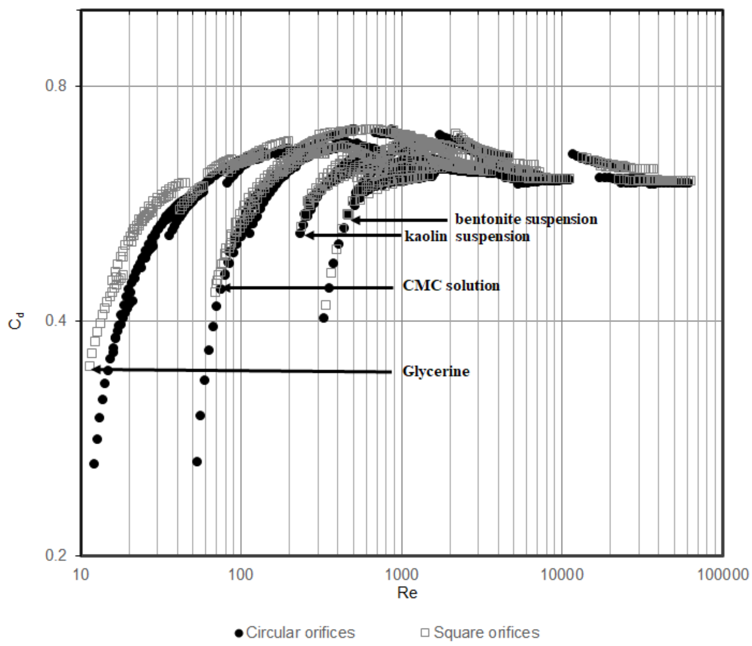

Figure 2. Effect of shape for circular and square orifices

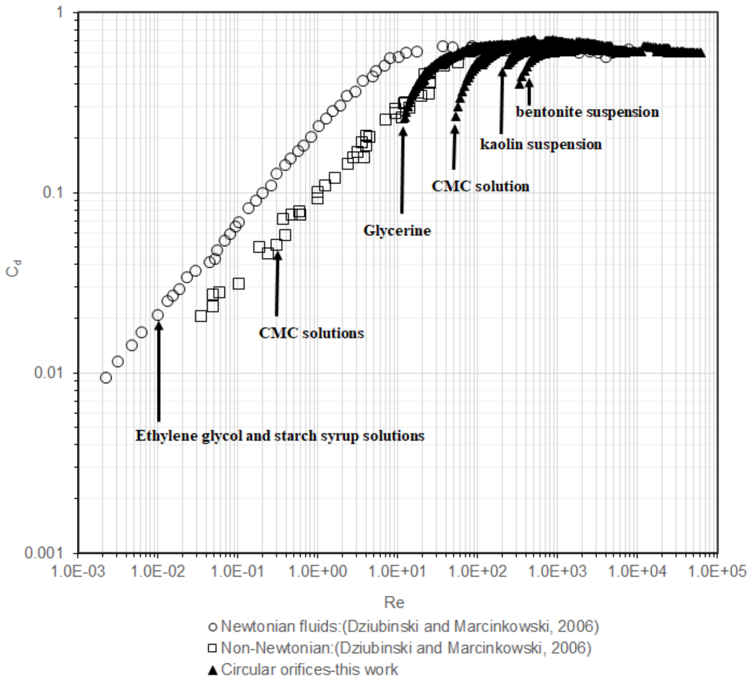

Figure 3. C_d vs Re for Newtonian and non-Newtonian fluids for L/d of 0 (Dziubinski and Marcinkowski, 2006)

4. CONCLUSIONS AND RECOMMENDATIONS

The Re values for square orifices are lower than the Re values for circular orifices for the viscous Newtonian fluids in the laminar region. In laminar flow, the Re values for Newtonian fluids start approximately from Re=10, for CMC solution from Re=50, for kaolin suspensions from Re=250 and for bentonite suspensions from Re=350. These values are similar for the two shapes of orifices. There is no difference in Re values within the turbulent region and values ranged between 10 and 80000 for both orifices. The average C_d values for all the orifices used here in turbulent flow is 0.62. This work extends the study of circular orifices flow rate measurement that was published by Dziubinski and Marcinkowski, (2006), as circular and square orifices were used to measure the discharge of Newtonian, and non-Newtonian fluids exhibiting power law, Bingham and yield pseudoplastic behavior. From the results, it is clear that both viscosity and yield stress have an effect on the flow rate of non-Newtonian fluids through orifices. This will have to be investigated, so that the non-Newtonian and Newtonian data can be collapsed on to one master curve for the prediction of C_d value in a new application.

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