SAN JOSÉ STATE UNIVERSITY

DEPARTMENT OF MECHANICAL ENGINEERING

Buoyancy-Driven Flow

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1. Abstract

This project is a study of Buoyancy-driven flow by comparing the results for velocity, skin friction force, skin friction coefficient and volumetric flow rate between experiments and CFD simulations. The experiment was to measure the change in velocity in a pipe, due to a heated source increasing the temperature inside the pipe. Non-ideal conditions result in discrepancies in values between CFD and experimental values to be discussed.

2. Introduction

Buoyancy-driven flow is a common occurrence in many different natural and engineering systems. This effect occurs when there is a temperature gradient within a system. This temperature gradient then causes a density gradient within the fluid inside the tube. Due to the variations in temperature and density, a pressure difference is created within the tube, resulting in fluid flow. To study this phenomenon an experiment was conducted on 2 vertically oriented pipes of differing lengths where a temperature variation was induced. The results of the experiment were then compared to a simulation conducted using ANSYS Fluent.

3. Experimental setup

a. Initial Experiments

To test the effect of buoyancy driven flow, an experiment was conducted utilizing two varying lengths of PVC pipe. Both a 1.5 meter length and a 0.75 meter length of PVC pipe with a diameter of 38.1 mm (1.5 in) was wrapped in foam insulation to minimize the loss of heat in the experiment to the surrounding environment.

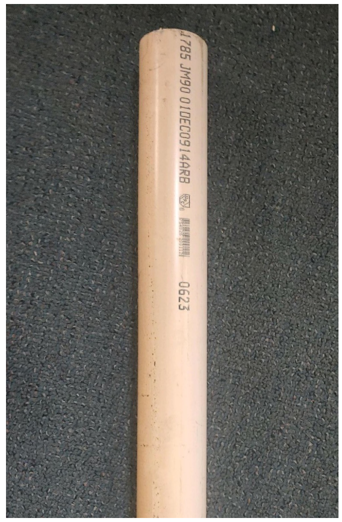

Figure 3.1. PVC pipe used in experiment.

The pipe was then attached vertically to a pillar to steady the experiment allowing consistent heating and reading of the results. Thermometers were placed in the base and the top of the pipe to measure the inlet and outlet temperature of the air.

Figure 3.2. Pipe fixture for 1.5 meter long pipe.

A space heater was placed at the base of the pipe to increase the temperature of the air inside the pipe from the inlet. The temperature difference between the inside of the pipe and the room will create a thermally driven flow due to the pressure variation. Boiling dry ice is then placed at the base of the pipe allowing it to be drawn through the interior. A Samsung Galaxy S21 smartphone is used to record a video of the smoke from boiling dry ice for the flow visualization. The velocity of the flow is estimated based on the vertical distance the smoke traveled measured by the ruler mounted on the wall and the time interval between image frames. This is accomplished by importing the video into Windows Video Editor and analyzing the number of frames it takes for the smoke to travel across the ruler. These frames are then referenced with the frames per second of the video to calculate a measurement of the velocity of the air exiting the pipe.

Figure 3.3. Pipe fixture for 0.75 meter long pipe.

The above experiment was then repeated utilizing a 0.75 meter length of PVC pipe with the same diameter.

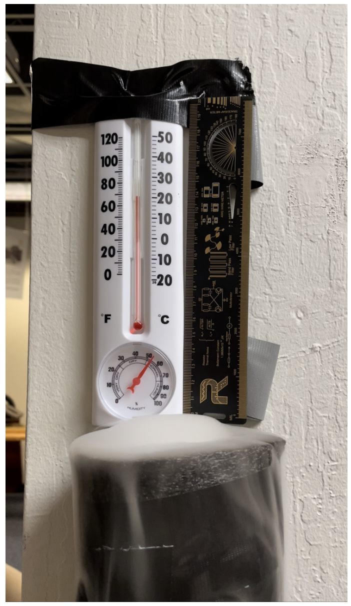

Figure 3.4. Flow visualization with dry ice.

However, there are three problems with this experiment setup. As Figure 3.4 shown, due to the density difference of CO_2 (dry ice) and air, the smoke traveled downward instead of upward after it exited from the top of the pipe. Also the thermometer mounted on the wall could not measure the inside temperature of the pipe properly. Lastly, the space heater did not heat the tube adequately. Hence, the improvement of the experiment is necessary.

b. Improved Experiments

To alleviate the density difference, incense was used instead. This is because while dry ice is made of CO_2 which is heavier than air, incense utilizes smoke that has similar density as air. This solved the problem of the visualized air flow from falling to the ground rather than rising up like intended.

Figure 3.5. Improved pipe fixture setup for the 0.75 meter long pipe.

Figure 3.5. Improved pipe fixture setup for the 1.5 meter long pipe.

Figure 3.6. Incense sticks used in experiments.

The space heater caused the heating inadequacy, because its heating distance was only about a third of a meter. This resulted in the bottom of the PVC pipe being 100°F while the top would only be about 2-3°F above room temperature. This problem was solved by using a heat shrink gun. The heat shrink gun performed similar to a hairdresser, and created temperatures at the top of the tube even higher than 85°F.

Figure 3.7. Heat shrink gun used in experiments.

Another improvement made was to alleviate the measuring inaccuracy of placing a thermometer at the top of the PVC pipe. An infrared temperature gun was used to measure the PVC's inside surface. This gave readings that were more consistent and reactive to when the heat was applied.

Figure 3.8. Infrared temperature gun used in experiments.

Average travel distance from three different portions of smoke were taken into account to estimate the velocity of the flow for both 1.5 m pipe and 0.75 m pipe. This can reduce the effect of potential estimation error.

4. Simulation setup

A comparison simulation to the practical experiment was conducted utilizing ANSYS Fluent. The internal fluid volumes of the varying pipe lengths were modeled in ANSYS with the included modeling software Spaceclaim. Upon completion of meshing, it was necessary to create named selections of the surfaces of the cylinders that would act as the inlet, wall and outlet of the modeled fluid.

To set up the simulation in ANSYS Fluent, both a laminar and k-omega model were used to compare results, with results being similar between both and laminar ultimately being chosen due to computational efficiency. Gravity was also assigned at -9.81 m/s^2. The following boundary conditions necessary for a successful simulation were applied to the following: an inlet vent, a perfectly insulated wall and a pressure outlet. A pressure inlet and outlet vent were also tested yielding identical results.

5. Results and discussion

a. Experiments

A video was recorded using a phone camera at 59.37 frames per second for both the 1.5 meter and 0.75 meter length PVC tubes. For each recording, three separate flows of smoke were analyzed frame by frame, to determine the velocity of each flow. The ruler placed in the background was used to establish a length scale to determine the amount the smoke moved between each frame and is shown in Figure 5.1. The speed was then calculated using the equation below in Figure 5.2.

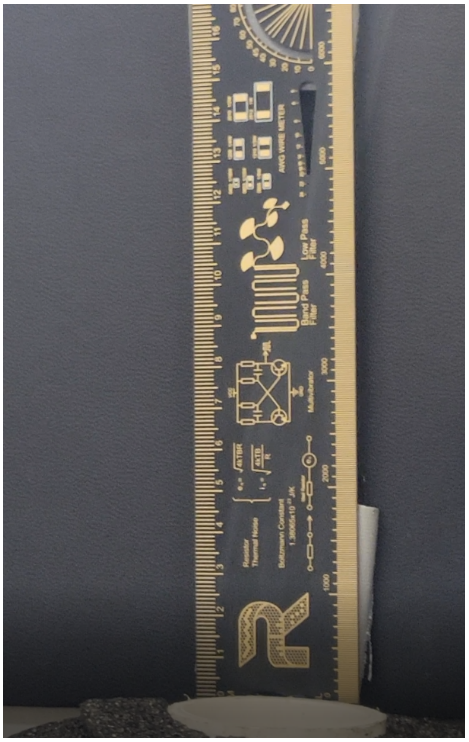

Figure 5.1. Ruler used to calculate the fluid velocity.

$$v = \frac{\Delta h(cm)}{Num.ofFrames}\frac{59.37Frames}{Second}\frac{1m}{100cm}$$

Figure 5.2. Equation used to calculate the fluid velocity.

The change in height was measured over 3-4 frames, using roughly the same part of the smoke each time. The speed was determined for three separate flows of smoke and averaged to determine the velocity of the flow through each pipe. The results for each pipe are shown below in Figure 5.3, with an average velocity of 1.029 meters per second for the 1.5 meter long pipe and an average velocity of 0.625 meters per second for the 0.75 meter long pipe. The volumetric flow rate for each flow was then determined by multiplying the average velocity by the cross-sectional area of the 1.5 inch diameter pipe.

Long Pipe (1.5m)		Diameter (in)	1.5	Diameter (m)	0.0381
Trial	Distance (cm)	Frames	Speed (m/s)	Top Temp (C)	Room Temp (C)
1	4.8	3	0.950	31.22	21.33
2	5.6	3	1.108	31.22	21.33
3	5.2	3	1.029	31.22	21.33
Avg Speed (m/s)	1.029	Volumetric Flow Rate (m3/s)		1.17E-03	

Short Pipe (0.75m)		Diameter (in)	1.5	Diameter (m)	0.0381
Trial	Distance (cm)	Frames	Speed (m/s)	Top Temp (C)	Room Temp (C)
1	2.5	3	0.495	29.33	21.33
2	4.3	4	0.638	29.33	21.33
3	5	4	0.742	29.33	21.33
Avg Speed (m/s)	0.625	Volumetric Flow Rate (m3/s)		7.13E-04	

Figure 5.3. Table of calculations made to determine the average velocity and volumetric flow rate.

Next, from the velocity and temperature measurements that were obtained calculations were performed to determine the skin friction coefficient for the flow inside the pipe. The Reynolds number for each flow was calculated based on the kinematic viscosity of the fluid, diameter of the pipe, and the average velocity of the smoke. The results of this calculation, shown below in Figure 5.4, indicate that the flow is laminar, as the Reynolds number for each flow is near or below the critical Reynolds number of 2300 for internal pipe flow.

air_density	1.184	kg/m^3
kinematic_viscosity	1.61E-05	m^2/s
dynamic_viscosity	1.90E-05	kg/(m-s)
T_amb	21.330	°C
T_short	29.330	°C
T_long	31.220	°C
g	9.810	m/s^2
h_short	0.750	m
h_long	1.500	m
beta	3.66E-03	K^-1
p_buoyancy_short	0.255	Pa
p_buoyancy_long	0.631	Pa
v_short	0.625	m/s
v_long	1.029	m/s
D	0.038	m
Skin Friction Calculations (Experiment)		
Re_D_short	1,481	laminar
Re_D_long	2,438	laminar
f_short	0.043	f=64/Re_D
f_long	0.026	
Friction head short	0.017	m
Friction head long	0.056	m
Friction short	0.197	N
Friction long	0.648	N

Figure 5.4. Calculations used to determine the skin friction coefficient and stack effect pressure difference.

Because the flow is laminar, the skin friction coefficient for the flow inside the pipe can be determined by the equation shown below in Figure 5.5. Based on the Reynolds number that was determined, the skin friction coefficient for the 0.75 meter pipe and the 1.5 meter pipe was determined to be 0.043 and 0.026 respectively.

$$f_{lam} = \frac{64}{Re_D}$$

Figure 5.5. Equation to calculate the friction coefficient for laminar internal flow [1].

While the friction coefficient is smaller for the longer pipe, the friction force for the longer pipe is larger than that for the shorter pipe, as expected. From the skin friction coefficient, the friction head was then determined from the equation shown below in Figure 5.6. Then the friction force was determined from the equation shown below in Figure 5.7, giving a friction force of 0.197 Newtons and 0.648 Newtons for the 0.75 meter and 1.5 meter pipe respectively.

$$h_f = f\frac{L}{D}\frac{v^2}{2g}$$

Figure 5.7. Equation used to determine the friction head of the pipe [1].

$$F_f = h_f \rho g$$

Figure 5.8. Equation used to determine the friction force of the pipe [1].

b. Simulations

The 1.5 m length tube was given a pressure differential of 0.614 Pa as calculated from the data provided by the experiment. This value was calculated with the equation $\Delta p = \rho_0 gh(\Delta T/T_0)$. This pressure differential yielded a fluid velocity of 0.81 m/s. With a cross-sectional area of $1.14\text{x}10^{-3}$ m the simulated volumetric flow rate of the 1.5 m test pipe was $9.235 \text{ x } 10^{-4}$ m^3/s. Utilizing the excel table shown in Figure 5.9 to calculate the experimental results for skin friction, the simulation yielded a skin friction coefficient of 0.033 and a friction force of 0.510 Newtons.

Skin Friction Calculations (CFD)		
v_short	0.6	m/s
v_long	0.81	m/s
Re_D_short	1,422	laminar
Re_D_long	1,919	laminar
f_short	0.045	
f_long	0.033	
Friction head short	0.016	m
Friction head long	0.044	m
Friction short	0.189	N
Friction long	0.510	N

Figure 5.9. Calculations used to determine the skin friction coefficient for the CFD simulation data.

The 0.75 m tube had a pressure differential of 0.25 Pa based on the experimental data. This yielded a fluid velocity of 0.60 m/s. This corresponds to a simulated flow rate of 6.84 x 10^{-4} m^3/s using the same cross-sectional area as calculated on the 1.5 m pipe. The skin friction coefficient of the 0.75 m pipe was 0.045 with a friction force of 0.189 Newtons.

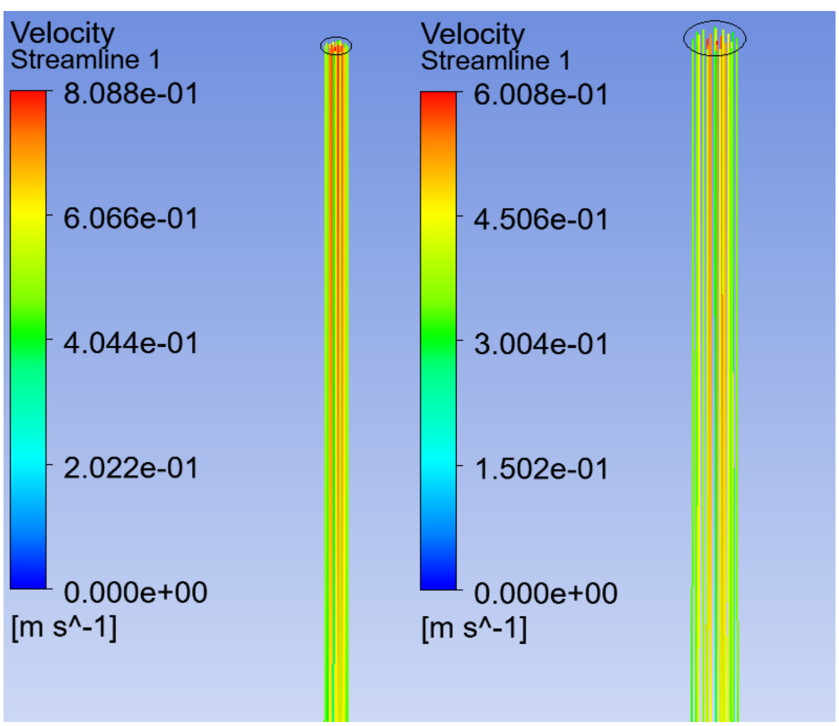

Figure 5.10. Fluid velocity in 1.50 m (left) and 0.75 m (right) pipes.

CFD Simul.	Fluid Vel. (m/s)	Vol. Flow (m^3/s)	Skin Frict Coef	Friction Force (N)
Short Pipe	0.6	6.84E-04	0.045	0.189
Long Pipe	0.81	9.24E-04	0.033	0.51

Figure 5.11. Volumetric flow rate, skin friction coefficient, and friction force results.

c. Discussion (including uncertainty analysis)

Reasons for discrepancy:

Using smoke for flow visualization brings in other gas into the pipe. The way to minimize the effect from this aspect is to change the smoke source from dry ice to burning incense as well as reducing the smoke amount introduced into the pipe. However even though the burning incense was closer in density to air than dry ice, it still is not completely the same as air. This is because the burning incense still introduces foreign particles into the air. The incense, albeit still being more similar to air density, is still a little bit heavier than air with the foreign particles.

Estimating velocity frame by frame from videos of the smoke is not accurate. This technique to determine the velocity of the fluid relied on determining the velocity of the fluid by eye using a ruler placed in the background of the video. Determining the velocity proved difficult using this method, as the fluid was difficult to see and it was often difficult to track the same portion of the flow as it traveled multiple frames. Many attempts to track the flow of individual streams of smoke proved difficult, as that very same stream may not be easily visible in subsequent frames, limiting the number of viable sections of the flow to determine the velocity from. With a larger sample size, the percentage error may be lower as three samples for each pipe length is not a very large sample size.

Though the foam provides insulation around the PVC pipe, it cannot create an ideal isothermal system. Heat within the PVC pipe generated by the heat shrink gun is still lost to the environment. This results in a lower than expected velocity for the air within the pipe. The temperature difference is lowered between inside the pipe and the ambient environment, and this results in a lowered pressure difference as well. With the lowered differential pressure, the air will not accelerate as fast and lower outlet velocity. When using the dry ice, it was observed that some of the fluid leaked out through gaps in the insulation, causing not all of the fluid to make it to the top of the pipe.

CFD analysis assumes ideal conditions, therefore error will be induced due to the analysis performed assuming ideal wall conditions that are perfectly insulated and no change in the composition of the air entering the pipe. The percent error for velocity, volumetric flow rate, skin friction coefficient, and friction force was calculated using the equation shown in Figure 5.11. The results are shown below in Figure 5.12, with a much larger percentage error for the 1.5 meter pipe as compared to the 0.75 meter length. This may be due to the problems with fluid leaking through the insulation, meaning as the pipe length is increased more and more of the fluid would leak through the insulation, introducing additional error into the experiment.

$$\%error = \left| \frac{V_{exp} - V_{CFD}}{V_{CFD}} \right| * 100\%$$

Figure 5.11. Equation used to determine the percent error.

	Velocity percentage error	Volumetric flow percentage error	Skin friction coefficient percentage error	Friction force percentage error
0.75 m Pipe	4.16%	4.24%	4.44%	4.23%
1.5 m Pipe	27.03%	26.7%	21.21%	27.05%

Figure 5.12. Table of percentage error calculations for velocity, volumetric flow rate, skin friction coefficient and friction force.

6. Summary and conclusions

The team successfully measured the fluid velocity of two PVC pipes of 1.5 m and 0.75m. The results of the experiment yielded flow velocities of 1.029 m/s and 0.625 m/s respectively. Performed

CFD analysis yielded results of 0.81 m/s for a 1.5 m pipe and 0.60 m/s for a 0.75 m pipe. This resulted in an error differential between the CFD and experiment of 27.03% for the 1.5 m pipe and 4.16% for the 0.75 m pipe. Experimental and CFD results were then used to calculate volumetric flow rate, skin friction coefficient and friction force values. The volumetric flow rate for the 1.5 m pipe was 1.17 x 10^{-3} m^3/s for the experiment and 9.24 x 10^{-4} m^3/s yielding an error differential of 26.7%. Tests on the 0.75m pipe yielded volumetric flow rates of 7.13 x 10^{-4} m^3/s on the experiment and 6.84 x 10^{-4} m^3/s, an error of 4.24%. The 1.5m pipe's skin friction coefficient was 0.026 for the experimental results and 0.033 for the CFD results, a resulting error of 21.21%. For the 0.75 m test, skin friction coefficients were 0.043 on the experiment and 0.045 from CFD, a difference of only 4.44%. Finally, the calculated friction forces on the 1.5 m pipe were 0.648 N for the experimental results and 0.51 N for the CFD results, a difference of 27.05%. For the 0.75 m pipe, the friction forces were 0.197 N for the experimental setup and 0.189 N for the CFD simulation, an error differential of 4.23%

Although there were errors in the initial experimental setup, they provided an opportunity to learn from the mistakes and improve upon tests. Although the experimental results were broadly similar to the CFD simulation, there is still room for experimental accuracy to be improved. To obtain more accurate results, an air flow meter can be used to measure the resultant changes to velocity and volumetric flow rate. This would eliminate the difficulty in assessing the proper velocity using frame counting, as well as remove the need to visually see the smoke particles in the air.

7. References

1. White, F. M. (2016). *Fluid Mechanics* (Eighth Edition). McGraw Hill LLC.
2. Ansys Fluent 2020 R2, Ansys® Academic Research Mechanical, Release 18.1