Influence of Orifice Diameter on Discharge Coefficient

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In this experiment, we observed the effects of orifice diameter on a tank blowdown's discharge coefficient. Using a pressure transducer and a thermocouple, we measured the change in pressure and temperature over time as air was released through orifices of diameters of 0.025", 0.055", and 0.125". The discharge coefficient quantifies how efficiently the air flows through the orifice. Due to friction losses, we expected that the discharge coefficient would increase as the orifice diameter increased, indicating higher efficiency. However, we found that the discharge coefficients for the small, medium, and large orifices were 0.776 ± 0.031, 0.789 ± 0.018, and 0.895 ± 0.025, respectively. While the discharge coefficient appeared to increase with increasing orifice size, the large uncertainties in the discharge coefficients of the small and medium orifices caused the ranges to overlap, meaning that they are not measurably different. We tested our assumption that the system was isothermal by comparing our data to an ideal isothermal system, and confirmed this assumption was valid and not a significant source of error. As a result, it appears that the discharge coefficient does not change significantly with these three orifices.

INTRODUCTION AND METHODS

In this investigation, we explored the dynamics of pressure and temperature in an air tank during a blowdown procedure. The purpose was to understand the effects of different size orifices on the process by measuring pressure and temperature and determining the change, if any, in the time constant of the system and the discharge coefficient. The discharge coefficient is a measure of how efficiently a fluid can flow through a constricted area. Mathematically, it is a ratio of the actual flow rate over the theoretical flow rate for that orifice.

The experimental apparatus consisted of a small pressure vessel with three measurement devices attached: a Bourdon pressure gauge (which measured the pressure in psig), a diaphragm pressure transducer (which measured the pressure in Volts), and a type K thermocouple. The output from the thermocouple was measured by a Klein multimeter configured to display the signal in degrees Celsius. Finally, three orifice sizes were used: 0.025", 0.055", and 0.125".

Figure 1: Experimental apparatus

First, it was necessary to calibrate the data from the pressure transducer using the Bourdon pressure gauge. Starting at 80 psi, the values reported by the pressure gauge and pressure transducer were recorded at decreasing intervals of 10 psi. To account for the transience of the system, the system was allowed to settle at each interval before the pressure measurements were recorded. In addition, measured voltage from the pressure transducer at each pressure was calculated by averaging the 100 samples taken each second. After performing this procedure three times, the linear calibration curve in Equation 1 was developed from the three replications (see also Figure 2).

$$P = (19.7\,V + 1.36) \pm 0.84 \text{ psi} \tag{1}$$

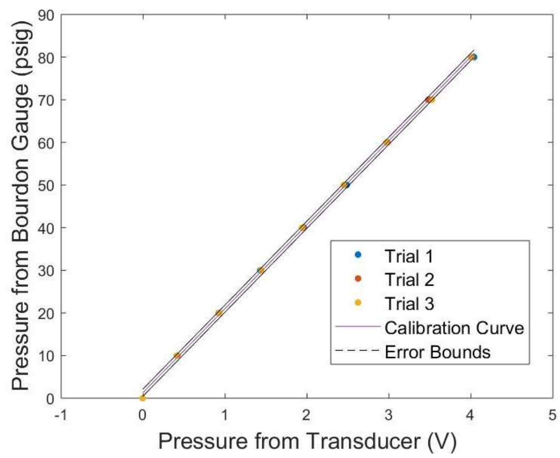

Figure 2: Calibration curve relating pressure measurements from the transducer and Bourdon gauge.

This calibration curve was used to adjust measurements from the pressure transducer from the blowdown tests.

Next, we performed a tank blowdown test with each orifice. The vessel was again pressurized to 80 psi. Once the exhaust value was opened, data from the pressure transducer and thermocouple were recorded using LabView until the tank was empty.

Before we analyzed the results of the tests, we extracted the data that was most useful by excluding measurements from before the value was opened. In addition, we excluded pressure values that were below 191.8 kPa, since Equations 2 and 3 below are only valid if the pressure is greater than that value [1]. Once the data was extracted, the time constant of the tank blowdown, τ, was found by curve fitting the pressure data according to Equation 2 using MATLAB's *lsqcurvefit* command [1].

$$P = P_0 e^{-\frac{t}{\tau}} \tag{2}$$

Using this time constant and properties of the tank, the discharge coefficient, C, was calculated by

$$C = \frac{V}{0.0404\, R\, \tau\, A_{valve}\sqrt{T_0}} \tag{3}$$

where V was the tank's volume, R was the gas constant, T_0 was the initial tank temperature, and A_{valve} was the area of the orifice [1].

It must be noted that Equations 2 and 3 implicitly assume that temperature remains constant during this process. To test this assumption, we compared our temperature data to what the data would look like if the system was purely isothermal and if the system was purely adiabatic. A description of the adiabatic process is given by:

$$T_{tank} = T_0 \left(1 + \frac{\gamma - 1}{2}\frac{t}{\tau}\right)^{-2} \tag{4}$$

where τ is the experimental time constant found in Equation 1 and γ is the specific heat ratio [1].

RESULTS AND DISCUSSION

For each orifice, the theoretical pressure decay was computed using Equation 2 and compared to the experimental pressure decay. As seen in Figure 3 below, air escapes the tank more quickly with a larger orifice, leading to a faster change in pressure. All three theoretical curves tend to overestimate the actual pressure for approximately the first half of the trial and underestimate the actual pressure near the end of the trial. However, the theoretical curves generally match the experimental curves well.

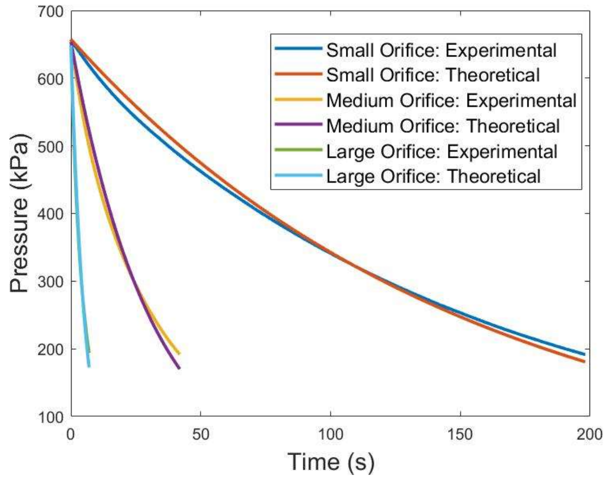

Figure 3: Pressure decay during tank blowdown with the small, medium, and large orifices, compared with the theoretical curves.

The resultant time constants and discharge coefficients for each orifice, as well as their uncertainties, are presented in Table 1.

Table 1: Resulting time constant and discharge coefficient for each orifice

Orifice Size (in)	Time Constant, τ (s)	Discharge Coefficient, C
0.025	153.4 ± 0.48	0.776 ± 0.031
0.055	31.1 ± 0.39	0.789 ± 0.018
0.125	5.29 ± 0.14	0.895 ± 0.025

It is apparent that the time constant decreases drastically with increasing orifice diameter. This is reasonable since, again, the larger the orifice, the faster the pressure. This is illustrated in Figure 3, which clearly shows the decreasing time needed to empty the tank.

From the mean values of discharge coefficient in Table 1, it appears that C increases with increasing orifice size. Theoretically, this is reasonable. Due to friction losses as air in the tank attempts to exit through a small hole, the air flows less ideally through the smallest orifice than the largest orifice. However, our data does not necessarily support that. The uncertainties in the discharge coefficients of the small and medium orifice overlap, meaning that they are not measurably different. On the other hand, C for the largest orifice lies outside of the range of either of the other two orifices, leading us to conclude that has a significantly different discharge coefficient value. Therefore, our results are not conclusive.

As mentioned previously, we initially assumed that the tank blowdown was an isothermal process. However, it was important to check this assumption before eliminating it as a source of error. In Figure 4, the three processes are compared for each orifice. In the beginning of each blowdown, the system exhibits adiabatic behavior/temperature appears to decrease adiabatically before settling into an isothermal process/following an isothermal curve. As a result, the data looks drastically different than the adiabatic results.

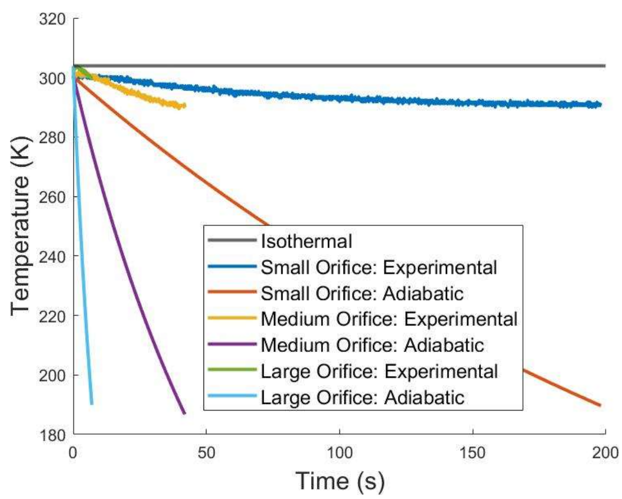

Figure 4: Comparing experimental blowdown process with theoretical isothermal and adiabatic processes using the small, and large orifices.

From Figure 4, it appears that the small orifice blowdown most closely matches the isothermal assumption. However, it is more helpful to compare the actual change in temperature over the blowdown to the change predicted by the adiabatic process.

Table 2: Change in temperature over the experimental process and the adiabatic process

Orifice Size (in)	Experimental Temperature Change (K)	Adiabatic Temperature Change (K)
0.025	-9.70	-111
0.055	-10.1	-114
0.125	-4.82	-114

As seen in Table 2, the blowdown with the largest orifice was the most isothermal process of the three. In comparison to the adiabatic temperature change, however, all three trials experienced very small temperature changes. Thus, it is reasonable to assume that the blowdown process is isothermal, and this assumption is not a primary source of error.

CONCLUSIONS

This experiment was conducted to observe the tank blowdown process using orifices of different diameters and to determine if those orifices influenced the time constant and discharge coefficient. It was found that the time constant decreases dramatically as the orifice size increases and allows the tank to empty more quickly, ranging from about 150 seconds for the small orifice down to 7 seconds for the large orifice. In addition, the discharge coefficients for the small, medium, and large orifices were 0.776 ± 0.031, 0.789 ± 0.018, and 0.895 ± 0.025, respectively. We concluded that the discharge coefficient did not change significantly with these orifice diameters, as the range of possible values for the small and medium orifices overlapped. In addition, we confirmed that assuming that the process is isothermal is valid, as the temperature data is nearly constant for most of the trial, leading us to conclude that this was not a primary source of error.

REFERENCES

1. Sabatino, D. and Smith, J. Lafayette College. (2020). *Laboratory Project #4: Pressure and Temperature Measurements*. Easton, PA.