Horizontal Vent Flow Modeling with Helium and Air

JAMES H. SHANLEY, JR.*
Hughes Associates Incorporated
2730 University Blvd.
Wheaton, Maryland 20902, USA

CRAIG L. BEYLER
Fire Science Technologies
3215 Donnybrooke Ln.
Cincinnati, Ohio 45239, USA

ABSTRACT

Experiments were carried out in a small scale compartment by introducing different mixtures of air and helium at the top of the compartment to physically model the flow of a buoyant fluid through a horizontal ceiling vent. The ratio of air to helium was used to vary the apparent temperature of the layer. The apparent temperature is the temperature at which air would have the same density as the buoyant layer mixture. In this way a temperature range of 300 to 1100°K was simulated.

It was found that when the layer depth was equal to or greater than the vent diameter the buoyant layer was stable and the discharge coefficient was within 15 percent or less of the expected value of 0.60. When the layer depth was less than the vent diameter the layer became unstable and the discharge coefficient decreased to as low as 0.18. It was determined that when the layer depth is less than the vent diameter a weir-type flow condition results where the exiting gases do not fill the entire opening. Previously horizontal vent flow was always treated as orifice-type flow with a discharge coefficient of 0.60.

INTRODUCTION

Buoyancy-driven upward flow resulting from the density difference of the products of combustion and the ambient air can be used to vent smoke and heated gases. The hot gases collect near the ceiling of the compartment resulting in the formation of a layer. The rate of flow of hot gases out of a ceiling vent is a function of the pressure difference across the vent created by the density difference of the hot layer gas and ambient air and the hot layer depth.

The first goal of this research was to physically model ceiling smoke vents using a helium and air mixture to determine the effect of vent size and layer depth on the flow rate of buoyant gases from the vent. The physical model was

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* Work performed at the Center for Firesafety Studies, Worcester Polytechnic Institute, Worcester MA. 01609

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designed to eliminate the entrainment of lower layer, ambient air into the rising plume from a burner by injecting a mixture of helium and air into the top of the compartment. Data generated from the experiments were analyzed to test existing theories for smoke ventilation as presented by Thomas and Hinkley [1,2], Spratt and Heselden [3], Heskested [4], and Rockett [5].

Secondly, conditions necessary for the phenomenon of vent failure were studied. When specific conditions exist, ambient air from the lower layer of the compartment becomes entrained in the exiting gas stream. This has the effect of reducing the efficiency of the vent by causing some fraction of the hot gases and smoke to be excluded by the denser lower layer ambient air which is drawn through the vent by entrainment. This is evident by a reduction in the discharge coefficient. The discharge coefficient is defined here as the ratio of the flow rate through the vent to the flow rate predicted by the Bernoulli equation. The flow rate out of the vent was assumed to be equal to the flow rate of air and helium being supplied to the compartment which was measured during the experiments. When a vent does not contain any ambient air, flow through it resembles flow through an orifice. As described by Zukoski [6], when the vent is not filled with hot gases, flow through it more closely resembles flow over a broad-crested weir. This is most likely to happen when the layer depth is less than the vent diameter. Zukoski has reported that when a weir-type flow condition exists in a horizontal vent, the discharge coefficient may be as low as 0.4. These results were obtained from work with salt water models of horizontal vent flow. The helium and air physical model was used here to validate the weir-type flow theory and provide additional data concerning the efficiency of a horizontal ceiling vent under these conditions.

Helium and air mixtures were fed into the top of a small scale compartment to study the flow of these gases out of a circular ceiling vent. The apparent temperature of the gases were controlled by the ratio of helium to air and allowed the experiments to be conducted without a heat source and heat losses. This method made it possible to simulate temperature conditions of 300 to 1100°K. However the available supply of helium and air placed an upper limit on the range of layer depth and vent diameters which could be examined because of the high flow rates required.

Slightly buoyant smoke from incense sticks was used to indicate the interface between the upper, buoyant helium and air layer and the lower, ambient air layer. The smoke accumulated directly below the buoyant layer and was continuous across the width of the compartment. Vent failure was visually indicated by the appearance of a smokeless column or cone of air directly below the vent.

EXPERIMENTAL APPARATUS AND PROCEDURE

As shown in Figure 1, the compartment was constructed with an open bottom and a vent in the center of the top. The

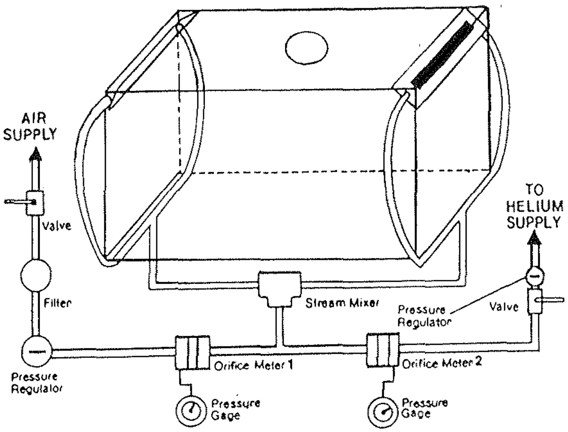

Figure 1. Experimental Apparatus

dimensions of the compartment were 0.914 m (3 ft) by 0.914 m (3 ft), and 0.508 m (20 in) high. It had a volume of 0.425 m^3 (15 ft^3). It was constructed of 6.35 mm (1/4 in) thick Plexiglass (polymethyl methacrylate). The circular vent was 5, 10, 15 or 20 cm (1.9, 3.8, 5.7 and 7.6 in) in diameter. The gas mixture entered both ends of two smaller corner compartments located along the entire length of two opposite sides. The opening from the small corner compartment to the main volume was covered by two layers of a porous material (furnace filter). These were designed to distribute the inflow of buoyant gases as evenly as possible across the opening and thereby reduce the velocity and turbulence of the stream emerging from the diffusers. The openings were at a 45 degree angle to the vent and were 4.6 cm (1.8 in) by 69 cm (27.1 in). Helium and air were supplied by pressurized cylinders and a high volume compressor respectively. The flow rate of the helium and air being supplied to the compartment was measured using critical orifice meters.

Three scales were placed inside the compartment to measure the layer depth. They were calibrated from 0 to 40 cm (0 to 16 in). The slightly buoyant indicator smoke was produced by incense sticks located at the open bottom of the compartment.

Figure 2 shows the apparent temperature of the gases as a function of the volume ratio of air to helium. The apparent temperature is the temperature at which air would have the same density as the helium and air mixture. The maximum apparent temperature is 2147°K which is produced by using pure helium at an ambient temperature of 300°K. However the limited supply of helium and flow rate capacity of the air supply system limited the experiments to a maximum apparent temperature of approximately 1200°K and a flow rate of 0.012 m^3/s (25 SCFM).

A series of experimental runs was carried out by setting the air flow rate at a particular value and then stepping up the helium flow rate, pausing for 15 to 90 seconds for the layer to stabilize. The data recorded for each run included the air and helium pressure at the upstream side of the critical orifice, and the layer depth.

Vent failure was indicated by an unstable buoyant layer which allowed a considerable amount of the heretofore stable smoke layer which had accumulated below the buoyant layer to become drawn into the gasses exiting the compartment by the vent. Vent failure became more pronounced when the smoke exiting the vent was excluded from the center of the vent by a smokeless column of air.

PRESENTATION AND DISCUSSION OF RESULTS

Data were collected during the experimental runs to physically model the flow of buoyant fire gases out of a ceiling vent. Since this was a new technique for modeling buoyant flows the data were used to compare the results of this physical model and technique to other physical models. The results and correlations developed by Thomas and Hinkley [1,2], and Spratt and Heselden [3] were used as a basis for comparison and rate flow estimation because a similar approach was used, both small and large scale experiments were conducted, and their results are accepted as reasonable estimates of horizontal vent flows. Agreement of these estimates with the experimental results would indicate that this air/helium physical model was dynamically similar to earlier physical models which have been scaled up for the purpose of ceiling vent design. Spratt and Heselden's work was specifically aimed at vent failure and the determination of a critical vent size above which entrainment of ambient air into the exiting gas stream would occur. They did this experimentally by decreasing the extraction rate (they used forced ventilation which was initially set high enough to cause entrainment) until entrainment was no longer observed for a given vent area. The results from their forced ventilation experiments were extrapolated and applied to buoyancy induced flow.

Figure 3 show the experimental discharge coefficient for the four vent diameters as a function of the apparent temperature of the buoyant gas mixture. For the 5 cm diameter vent where vent failure was not observed the average of the discharge coefficient was 0.59. This agrees well with the predicted value of 0.6 for orifice-type flow. As the vent diameter was increased the discharge coefficient decreased. For the 10, 15 and 20 cm diameter vents with layer depths ranging from 5 to 30 cm the average of the discharge coefficients was 0.49, 0.27 and 0.18 respectively. It was observed during the experiments that as the vent diameter was increased the buoyant layer became unstable and increasing amounts of the smoke layer below the buoyant layer was drawn up through the vent. Agreement of the 5 cm and non-failure 10 cm vent diameter results with the predicted indicates that this apparatus adequately models the physical phenomena of natural smoke venting within the experimental

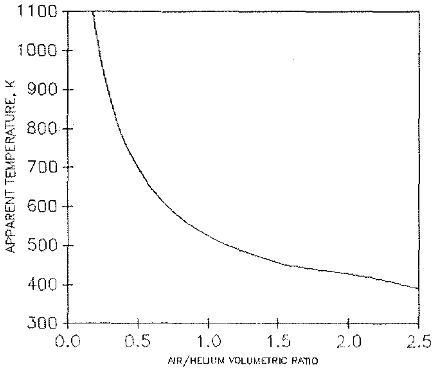

Figure 2. High Temperature Simulation by Air/Helium Mixtures

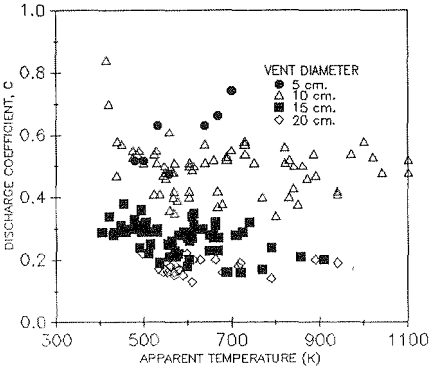

Figure 3. Experimental Discharge Coefficients

limits.

These results indicate that as the diameter of the vent increases for a given layer depth, the discharge coefficient decreases. A decreasing discharge coefficient could indicate one or more of the following: unaccounted-for gases (air) have been entrained into the venting gas stream (vent failure), viscous or flow geometry effects are significant, or turbulent effects due to approach stream velocity. It has been reported by Zukoski [6] that all but the entrainment effects associated with weir-type flow and vent failure are usually in the 5 to 10 percent range and therefore are not felt to be responsible for the larger deviation seen here.

The entrainment could be due to one of two factors. The expected reason is that as the vent becomes larger while the layer depth remains essentially the same, the vent is approaching a failure condition and flow through it is no longer orifice-type. Vent failure can be manifested in two ways depending on the layer depth. When the layer depth is smaller than the vent diameter (ratio of diameter to layer depth, d/H, is less than 1) the flow through the vent will be similar to that of fluid across a broad crested weir and the gas may not fill the whole opening resulting in air being entrained into the stream. In this case a discharge coefficient in the range of 0.4 has been reported [6]. When the layer depth is greater than the vent diameter, too high an extraction rate will draw up air from underneath the layer into the vent. This is a situation where the layer is not thick enough for only layer gas to be extracted through the vent and entrainment results. This was not observed in these experiments and had been reported only by Spratt and Heselden [3]. This is because they used forced ventilation. It is felt that the flow rate through the vent induced by buoyancy only is insufficient to cause this type of failure since it was not observed in these experiments.

The other explanation for the decreasing discharge coefficient with increasing vent size is that the larger flow rates required to sustain a layer in the compartment are entraining ambient air before reaching the vent. It was observed during the experiments that a greater amount of turbulence was present during the 15 and 20 cm diameter vent runs. The premise of this study was that the increased turbulence is due to the onset of vent failure and that ambient air entrainment is minimized by apparatus design. However observation showed that the 45 degree angle of the stream diffuser may have caused a portion of the air/helium stream to go below the interface. In the same manner as a fire plume, this stream of buoyant gases would have entrained additional ambient air while it was below the interface which would increase the volume of the layer after the buoyant gases rise back into the layer.

Figure 4 shows the predicted and experimental Reynolds number at the vent as a function of apparent temperature for three vent diameters. The experimental Reynolds number was calculated using the velocity through the vent obtained from the experimental data, the vent diameter and the kinematic viscosity of the helium/air mixture. The predicted Reynolds number was calculated using the velocity obtained from the Bernoulli equation. The experimental Reynolds numbers ranged from 1500 to 3000. The results indicated that the low discharge coefficients were not the result of viscous effects at the vent.

The Richardson number was calculated using the average velocity of the gases leaving the diffuser and the density difference between the helium/air mixture and the ambient air. The average of the Richardson number at the diffusers for the 10, 15 and 20 cm diameter vents were 64.6, 49.9 and 41.7. The value of the Richardson number decreased as the diameter of the vent increased, but the minimum Richardson number was not less than 20. The decreasing Richardson number indicates a greater amount of turbulent mixing of the horizontal layers near the diffusers (buoyant helium/air upper layer and lower ambient layer) but it did not approach the critical value of 1.0 where horizontal layer mixing is considered significant [7]. Analysis of the Richardson number indicates that the small discharge coefficients were not caused by turbulent mixing of the ambient air and buoyant layer near the diffusers.

In the absence of viscous or horizontal mixing effects two other possible explanations were considered to be responsible for the low discharge coefficient, one of which was experimental. The basic assumption made to measure the flow out of the vent was that this outflow was equal to the inflow of the air/helium mixture. The experimental design was such that additional air may have been added to the layer by entrainment. Unfortunately the experimental data did not provide a means of quantifying this effect, although it was felt to be secondary. The reason for the low discharge coefficients was primarily the weir-type flow through the vent. In weir-type flow the buoyant gases flow out through an outer, annular area of the vent while ambient air occupies the inner area. Depending on several conditions including inlet area (compartment tightness), the ambient air may flow counter- or co-currently with the exiting gas stream. Weir-type vent flow is considered to be a primary cause of vent failure.

Vent failure was noted in many of the experimental runs and in all these cases the vent diameter to layer depth ratio (d/H) was greater than 1. Figure 5 shows the resulting discharge coefficient as a function of the d/H ratio. When d/H was less than 1.0 orifice-type flow occurred and the discharge coefficient tended toward 0.60. As the d/H ratio increased and became greater than 1.0, resulting in weir-type flow, the discharge coefficient steadily decreased.

CONCLUSIONS

The experimental design and procedure used in these experiments were successful in physically modeling buoyant gas flow from horizontal vents. This model was designed to eliminate the entrainment of air into the rising plume from a burner by injecting a mixture of helium and air into the top of the compartment. To a large extent this was accomplished. Difficulty arose when using the high end of the range of flow rates. The gas mixture stream may have entrained ambient air because it did not remain in the layer. This was due to the 45 degree angle between the face of the diffusers and the ceiling of the compartment which imparted a downward direction to the gas mixture stream as it left the diffusers. The momentum of this portion of the stream, which increased with flow rate, caused it to drop below the layer where it may have entrained additional air before rising back into the layer. This was evidence by the experimentally determined discharge coefficient which decreased as the vent was made larger. However the magnitude of unexpected entrainment was not felt to be sufficient for causing discharge coefficient which were found to be in the range of 0.20 to 0.30.

Work done with salt water models has suggested that when the layer depth is less than the horizontal vent diameter the vent will not longer act as an orifice. Flow through the vent will more closely resemble that of flow over a broad crested weir. In the case of a horizontal vent a hollow cylinder of fire gases will rise through the vent while

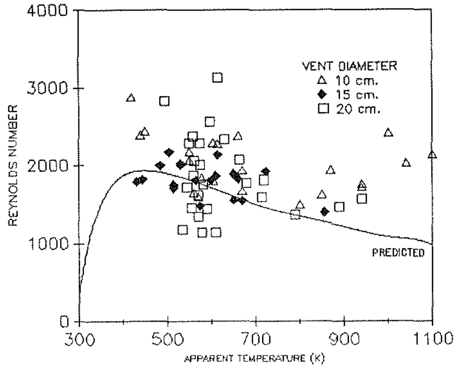

Figure 4. Reynolds Number at Vent

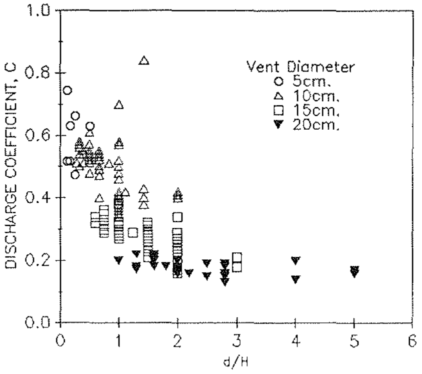

Figure 5. Effect of d/H Ratio on C

ambient air fills the inner space. Depending on the conditions in the fire compartment such as the amount of inlet area, the air may flow counter- or co-currently with the exiting fire gases.

A result of considering weir-type flow rather than orifice-type is that the discharge coefficient will be less than the commonly used value of 0.60. Limited previous research had shown that the discharge coefficient may decrease to 0.40 or less. The results of these experiments support this theory and have shown that as the difference between the layer depth (d) and the vent diameter (H) increases (increasing d/H), the discharge coefficient decreases. In the experimental model a value as low as 0.18 resulted when the layer depth was less than one-half of the vent diameter (d/H = 2). Physically a reduced discharge coefficient means that less of the geometric vent area is being used to vent fire gases and that the efficiency of the vent is reduced.

Conclusions to be drawn from this work include the following:

1. The technique of using helium and air mixtures to simulate buoyant layer development and physically model flow through vents is practical at a laboratory scale. Anything larger will entail using rather large quantities of difficult to recover helium.

2. Being able to physically model horizontal vent flows in the absence of heat transfer considerations simplifies the analysis and allows easy observation of smoke layer and venting.

3. The data yielded by this physical model are an accurate representation of the dynamics of horizontal venting within the normal limits of experimental precision. Enough data points were collected under different conditions to establish this degree of confidence and it is felt that the data could be easily reproduced.

4. When the layer depth is less than the vent diameter (d/H > 1) weir-type flow conditions will result. Under the weir-type flow the vent is considered to be failing because the entire vent is not filled with layer gases and ambient air occupies the remainder of the area. Failure will become more pronounced as the d/H ratio increases.

5. Weir-type flow conditions will cause the discharge coefficient to be reduced. These experiments produced discharge coefficients as low as 0.18. It is felt that within normal limits of experimental error and accounting for some unexpected entrainment, the conclusions of these experiments are valid for full scale horizontal vents. Weir-type flow through full scale horizontal vent will cause the discharge coefficient to be less than 0.6. Discharge coefficients for full scale vents under weir-type flow condition have not been reported in the literature or determined by these experiments.

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NOMENCLATURE

C = discharge coefficient
d = vent diameter
H = layer depth

KEYWORDS

Horizontal vent flow, horizontal vent failure, smoke behavior, physical model, discharge coefficient.