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Characterisation of the Plug-holing Phenomenon for the Exhausting of a Low Density Gas Layer

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Abstract

This paper presents some results of a study carried out in order to quantify the critical condition associated with the plug-holing phenomenon. The plug-holing is defined when a dip appears on the free surface of a fluid draining from a container. Experiments and numerical simulation were carried out for different values of the basic parameters of the problem : the initial height and the density of the drained fluid, the size and the shape of the vent for draining. A theoretical model is proposed and compared with experimental and numerical data.

Introduction

For fire engineering problems, the term plug-holing is generally used to characterise the extraction of fresh air through a layer of hot smoke under the effect of a significant transverse extraction. For practical applications, few data are available on this problem. The more suitable quantitative information comes from Heselden [1] who indicated that in order to keep a hot layer stratified on a ceiling, the mechanical flow rate of extraction must be maintained below a critical value Q_c defined by :

$$Q_c = 1.7\left(gh^5 T_0 \Delta T / T_s^2\right)^{1/2} \qquad (1)$$

In this formula, g is the gravity constant, h and T_s are respectively the height and the temperature of the hot smoke layer and T_0 the temperature of fresh air below the hot layer.

In order to bring to the fore the plug-holing phenomenon, Lubin and Springer [2] and Turner [3] studied the natural draining of a tank filled with two liquids of different densities. As shown on figure 1, they noticed that a dip appears on the free surface of the drained liquid. They described the critical condition at which the dip on the liquid surface reaches the level of the bottom of the container and the drain.

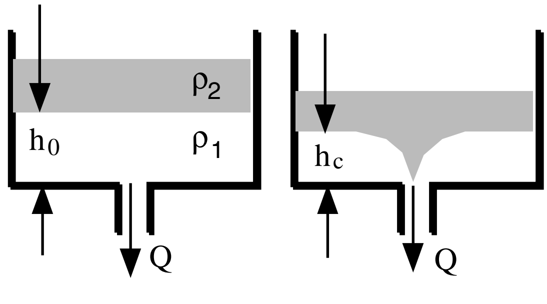

Figure 1. Experiments from Lubin and Springer [2]

In their article, Lubin and Springer show the existence of a relation between the volumetric flow rate Q, the densities of the two liquids ρ_1 and ρ_2, the drain diameter d and the critical height h_c associated with the plug-holing appearance (equation 2). In addition, they give a set of experimental results confirming this relation but obviously limited to a natural draining, i.e., only under the effect of gravity and without any mechanical extraction.

$$\frac{h_c}{d} = 0.69\left[\frac{Q^2}{(1-\rho_1/\rho_2)gd^5}\right]^{1/5} \qquad (2)$$

Turner found the same results from experimental tests with a slightly higher coefficient : 0.83 instead of 0.69.

In this paper, an analysis based on the Lubin and Springer theory is proposed to predict analytically the critical condition in the case of a low density gas exhaust. Experimental and numerical simulations are also carried out and compared with the model.

Theoretical approach

At first, let us consider that the pressure p_c at any point of the interface between the two gases is due to hydrostatic pressure :

$$p_c = p_a + \rho_1 g h_c \qquad (3)$$

At the instant prior to the dip formation, the flow is supposed steady. The initial depression (dip) on the surface develops so rapidly as to reach into the drain instantaneously.

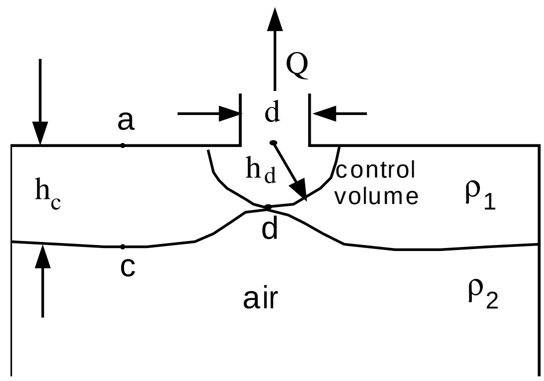

Figure 2. Formation of a dip

At the instant of the formation of the initial depression, the mass conservation for the hemispherical control volume shown on figure 2 may be expressed by :

$$Q = 2\pi U h_d^2 \quad (4)$$

The Bernoulli equation along a streamline just above the interface gives :

$$p_c - \rho_1 g h_c = p_d - \rho_1 g h_d + \frac{1}{2}\rho_1 U^2 \quad (5)$$

Equations (3), (4) and (5) may be arranged to yield :

$$h_c = h_d - \frac{Q^2}{8\pi^2 g\left(1-\rho_2/\rho_1\right)h_d^4} \quad (6)$$

In order to eliminate the height of the dip h_d from the above expression, we used the assumption that the dip grows very rapidly. Thus, we supposed that at the instant of the dip formation it can be written :

$$\left[\frac{dh_c/dt}{dh_d/dt}\right] \approx 0 \quad (7)$$

Equations (6) and (7) then give :

$$\frac{h_c}{d} = k\left[\frac{Q^2}{gd\left(\rho_2/\rho_1 - 1\right)}\right]^{1/5} \quad (8)$$

Actually, the constant k is 0.9 for Heselden, 0.83 for Turner and 0.69 for Lubin and Springer.

Means of study

Experimental set-up

For experiments, a model is set up to simulate exhausting of smoke by a vent under natural conditions.

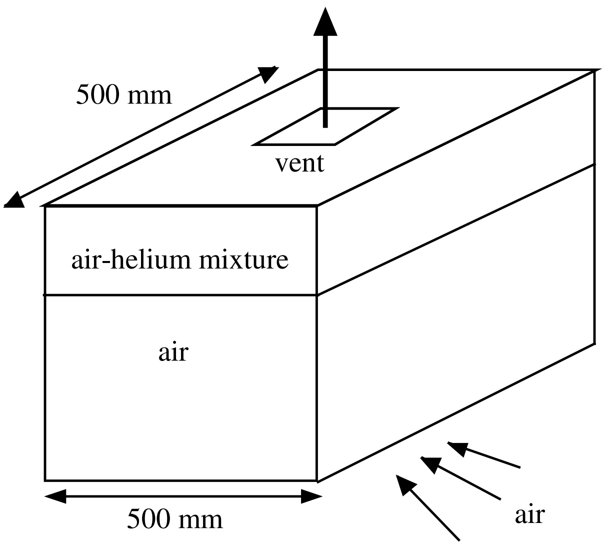

Figure 3. Experimental set-up

The model consists of a simple Plexiglas rectangular box with a vent on the upper face and an opening equal to the horizontal section on the lower part The main difference between the Lubin and Springer experiments and the present one is that they used two liquids with different densities whereas in our case two gases with an higher density ratio (air and helium) are used. Moreover in the present case, the exhaust of the gas is through the top of the tank instead of the bottom for the case of liquids.

Numerical simulation

The software used for simulations is CFX4. It is a finite volume code solving a set of transport equations. Numerical simulations have been carried out to be compared with the experiments done previously.

Results

Theoretical critical conditions

The flow velocity U of the mixture going out through the opening can be found by a simple application of the Bernoulli equation. U can be expressed as :

$$U = \sqrt{\frac{2gh(\rho_{air} - \rho_{mix})}{\rho_{mix}}} \quad (9)$$

with h the height of the mixture layer, ρ_{air} the density of air and ρ_{mix} the density of the air-helium mixing.
At first, if we consider that there does not exist any plug-holing phenomenon, the draining time of the mixture is given by :

$$T_{draining} = \frac{S}{s}\sqrt{\frac{2h_0}{g(\rho_{air}/\rho_{mix} - 1)}} \quad (10)$$

with S the surface of the whole interface area, s the surface of the vent and h_0 the initial height of the mixture layer.
In addition, it is possible to find the critical height when the air goes through the mixture layer. It happens when the draining mass flow reaches the critical value given by equation (8). The critical height theoretically depends only of the vent cross-section : h_c is simply given by :

$$h_c \approx 0.75\sqrt{s} \quad (11)$$

The following tables show the theoretical results obtained with the model for different initial configurations :

Vent sect (m^2)	0.01	0.01	0.01	0.01	0.01	0.01
h_o (m)	0.5	0.5	0.3	0.3	0.2	0.2
Helium %	100	50	100	50	100	50
Ini speed (m/s)	7.84	2.73	6.07	2.11	4.96	1.72
$T_{draining}$ (s)	3.19	9.17	2.47	7.10	2.02	5.80
h_c (m)	0.075	0.075	0.075	0.075	0.075	0.075
T_c (s)	1.95	5.61	1.23	3.55	0.78	2.24

Vent sect (m^2)	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
h_o (m)	0.5	0.5	0.3	0.3	0.2	0.2
Helium %	100	50	100	50	100	50
Ini speed (m/s)	7.84	2.73	6.07	2.11	4.96	1.72
$T_{draining}$ (s)	12.76	36.67	9.88	28.41	8.07	23.19
h_c (m)	0.038	0.038	0.038	0.038	0.038	0.038
T_c (s)	9.26	26.61	6.38	18.35	4.57	13.14

Table 1. Theoretical values of critical parameters

Visualisations

It is possible to visualise the plug-holing phenomenon at the interface between the two different gases by initially introducing particles into the air-helium mixing. The picture in figure 4 shows a critical condition for one of the experiments.

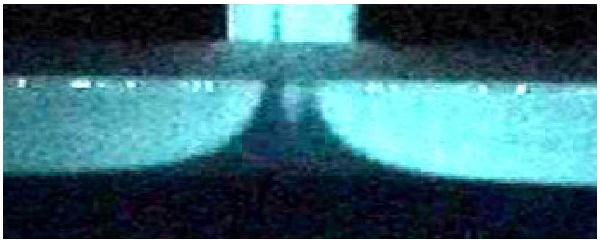

Figure 4. Critical condition (plug-holing)

It shows clearly that the visual interface between the mixture and the air is sharp and clean. Practically, when the dip appears, the critical height of plug-holing is assessed by a visual detection.
For hight density mixtures close to that of the air, the interface is not so sharp and interface instabilities appear as shown on the picture of figure 5. In practice, for helium volume fractions below 0.25, it becomes hazardous to determine the critical height of the mixture layer because it is difficult to visualise exactly the time of the dip formation.

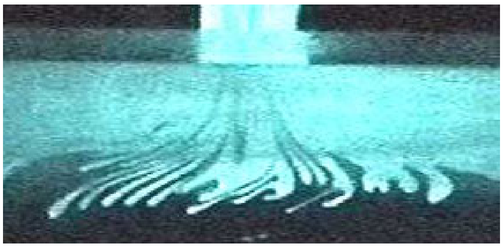

Figure 5. Interface instabilities for low densitiy difference between air and smoke

Experiments and numerical simulations

To validate the theory, experiments have been carried out with different shapes of vent (rectangular or square), different size of the vent cross-section (35*35, 50*50, 70*70, 100*100 mm) and different densities (from 0.163 to 0.95 kg/m^3).

Influence of the initial height

Table 2 shows the results obtained by CFD and experiments for different initial heights of the mixture layer. The critical height is not greatly influenced by the initial height as expected by the theory.

Section (cm^2)	h_o (m)	Helium %	Critical height (cm)		
			Theor.	Experim.	CFD
25	0.5	100	3.76	4.0	3.8
25	0.3	100	3.76	3.7	3.7
25	0.2	100	3.76	3.7	3.4
25	0.3	50	3.76	3.7	3.8
25	0.2	50	3.76	3.7	3.7
100	0.5	100	7.52	5.0	-
100	0.3	100	7.52	5.2	-
100	0.2	100	7.52	4.5	-
100	0.3	50	7.52	5.2	-
100	0.2	50	7.52	4.8	-

Table 2. Theoretical, experimental and computed critical heights for different conditions

Influence of the vent geometry

For these experiments, the 25 cm^2 and the 100 cm^2 vent sections have been tested for a square and a rectangular shape. The length ratio is equal to 2 for the rectangular shape. As shown in table 3, the experiments show that the geometry has no influence on the critical condition.

Section (cm^2)	h_o (m)	Critical height (cm)		
		Theor.	Exp. Squar	Exp. rect.
25	0.5	3.76	4.0	4.0
25	0.3	3.76	3.7	3.7
25	0.2	3.76	3.7	3.7
100	0.5	7.52	5.0	5.0
100	0.3	7.52	5.2	5.0
100	0.2	7.52	4.5	4.5

Table 3. Influence of the vent geometry (100% helium for all tests)

Influence of the vent section

Experimental and numerical results obtained for different vent cross-sections are presented in table 4, In both cases, it can be seen that the critical height increases with the size of the vent. Nevertheless, it does not increase in the same proportion as expected from the theory. This is probably due to the fact that, at the moment of the dip formation, the speed at the vent is slower than the speed at the critical time used in theory.

Section (cm^2)	Critical height (cm)		
	Theor.	Experim.	CFD
12.25	2.63	3.3	3.2
25	3.76	3.7	3.7
49	5.26	4.6	3.8
100	7.52	5.0	5.2

Table 4. Influence of the vent section (100% helium for all tests)

Influence of the smoke density

Table 5 shows that for helium volume fractions between 0.5 and 1 (and for a given cross-section), the critical height does not depend on the density according to the theory. For mixture densities close to that of air, the dip formation seems to occur from a greater height. This is probably due to the unstable interface which allows more penetration of the air through the mixture. The critical height observed is then higher for the low-density mixtures. On the other hand, the CFD simulations are very close to the experiment for the volume fraction of helium values contained between 0.5 and 1. For lower values, the critical height does not increase for the CFD simulations. As the theoretical model, CFD predictions show that the critical height does not depend on the density.

Section (cm^2)	Helium %	Mixing (kg/m^3)	Critical height (cm)		
			Theor.	Experim.	CFD
25	100	0.163	3.76	3.7	3.7
25	68	0.490	3.76	4.0	3.7
25	50	0.674	3.76	3.7	3.8
25	34	0.837	3.76	4.4	3.8
25	22	0.959	3.76	4.8	3.8
100	100	0.163	7.52	5.0	5.2
100	50	0.674	7.52	5.2	5.2
100	28	0.898	7.52	5.5	5.2

Table 5. Influence of the smoke layer density

The graph in Figure 6 presents a comparison between theory and experiment. Times for plug-holing appearance and for total draining are plotted as function of the mixture density.

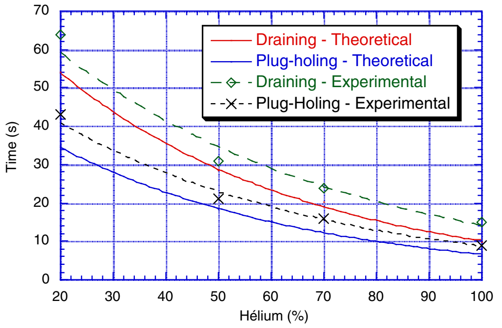

Figure 6. Time of plug-holing for different densities (h_0=300mm)

Generalised plug-holing law

Few experiments with forced ventilation have been also carried out on the model tank previously used for the study of buoyancy driven flows. A fan at the square exhaust vent of 25cm^2 with a constant volumetric flow rate has been set up. These experiments have been carried out in order to evaluate the critical flow rate (plug-holing appearance) for a forced extraction and then, to extend and generalize the study.

Figure 7 underlines the relationship between the gas densities, the critical flow rate and the critical depth of plug-holing with the data extracted from the experiments carried with natural and forced exhausting, and from the CFD simulations carried out with natural extraction.

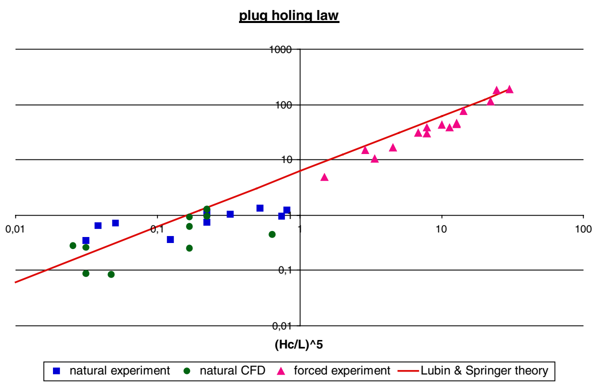

Figure 7. Generalised plug-holing law

The natural and the forced ventilation cases seem to follow a similar law, even if the points for the natural one are more scattered than the forced one from a straight line. The CFD simulations are close to the experiments.

Conclusion

A study have been carried out in order to characterise the critical conditions associated with the plug-holing appearance. Both theoretical, numerical and experimental approaches have been used to evaluate the critical parameter in the case of low gas density exhausting. A good agreement appears between experimental and numerical results. In particular, it seems that the CFX software well simulates flows driven by buoyant forces. The proposed empirical model (based on the Lubin & Springer theory) is also in a satisfactory accordance with experiments and calculations.

The critical height (height of th gas layer at which the plug-holing appears) is then given by the following relationship :

$$\frac{h_c}{d} = 0.725\left[\frac{Q^2}{gd\left(\rho_{air}/\rho_{mix} - 1\right)}\right]^{1/5} \qquad (12)$$

and the critical volumetric flow rate for a smoke layer with a depth h_s and a density ρ_s, is given by the following relation :

$$Q_c = 2.2\left(gh_s^5\Delta\rho/\rho_s\right)^{1/5} \qquad (13)$$

On the other hand, experiments have shown that in the case of smoke extraction, it is better to use several small vents than one big vent (with the same area of opening) in order to reduce the depth of plug-holing and to extract the smoke more efficiently.

Finally, it is encouraging to notice that a general law for the plug-holing critical conditions can be built in both cases of natural and forced draining.

References

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