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The Emptying-box problem with a baffle of different porosity percentages

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ABSTRACT

This research studies the Emptying-box problem with a porous baffle just behind the entrance opening. A theoretical model is extended to include the effect of a porous baffle, and the theoretical model taking account of porosity establishes the connections between two typical unidirectional displacement flow types. The salt-bath technique is employed to conduct the experiments using an acrylic reduced-scale model. Dye attenuation technique is used to analyze the light intensity data derived from the recorded images of experiments. According to the baffle porosity percentage (ϕ), the experiments are categorized into two series, EM(79%) and EM(60%). Each series respectively includes three different opening area ratios, which are 1, 0.5 and 0.33. Experimental results show that emptying processes for the cases with a baffle of the larger porosity percentage consist of emptying the dense layer and emptying the mixed layer, but there is only one process of emptying the dense layer for the cases with a baffle of the smaller porosity percentage. Experimental results are in reasonable agreement with the extended theoretical model developed in this research. Two extreme cases, those with and without an impenetrable baffle, are included in this paper to represent two typical flow types of the horizontal inflow denoted as EM(H), as that with $\phi = 0\%$, and the vertical inflow denoted as EM(V), as that with $\phi = 100\%$, i.e. the unidirectional classical displacement flow and the displacement flow with interfacial mixing. As the porosity percentage increases, the emptying time for the dense layer decreases, but the emptying time for the whole box tends to increase. The emptying time for the dense layer decreases, when the total effective opening area or the reduced gravity increases for the cases having the same porosity percentage. The initial interfacial height of the mixed layer increases, as the baffle porosity percentage increases for the cases having the fixed total effective opening area, or the total effective opening area increases for the cases with the same baffle porosity percentage. The initial buoyancy of the mixed layer is dependent on the penetrative entrainment flow rate from the dense layer to the mixed layer and the emptying time for the dense layer. As the total effective opening area or the porosity percentage increases, experimental results show that the initial buoyancy of the mixed layer tends to increase, and the penetrative entrainment flow rate increases as well, but the emptying time for the dense layer decreases.

1. Introduction

The Emptying-box problem [1] is an extension of the Filling-box problem [2], and both problems often arise in industry and nature. The Emptying-box problem is the process of utilizing the buoyancy force between the inside and outside fluids to empty the fluid in the box. Characteristics of this problem are as follows: first, the density difference between the inside and outside fluids is small compared to the density of the inside or outside fluid, and secondly, two fluids are miscible.

Linden et al. [1] classified the natural ventilation flow as displacement and mixing ventilation patterns, according to the levels of openings in the space. The displacement flow pattern discussed by Linden et al. [1] is regarded as the classical one, as shown in Fig. 1(a).

Displacement ventilation has been used over the past few decades as an energy efficient approach, compared to conventional overhead mixing systems. Natural displacement ventilation is usually regarded as the unidirectional classical displacement flow without interfacial mixing (Linden [3]). But the inflow of natural displacement ventilation may induce a similar effect to that by mechanical underfloor air distribution systems (Refs. [4,5]), which have some interfacial mixing between two distinct layers, as shown in Fig. 1(b).

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Nomenclature

A^*	total effective area (m^2)
a_x	opening area at the location x (m^2)
B	buoyancy ($m^4\ s^{-2}$)
$b_j(z)$	radius of the jet flow (m)
C_d	discharge coefficient (–)
g	gravitational acceleration ($m\ s^{-2}$)
g'	reduced gravity ($m\ s^{-2}$)
H	total height of the space (m)
h	interface level (m)
I	light intensity (–)
i	pixel index (–)
L	distance away from the jet flow virtual origin (m)
M_T	momentum flux at the top opening ($m^4\ s^{-2}$)
Q	volumetric flow rate ($m^3\ s^{-1}$)
Q^*	penetrative entrainment volumetric flow rate ($m^3\ s^{-1}$)
$Q_j(z)$	idealized volumetric flow rate of the turbulent jet flow ($m^3\ s^{-1}$)
$Q_{jp}(z)$	volumetric flow rate of the turbulent jet flow past a porous baffle ($m^3\ s^{-1}$)
S	cross-section area (m^2)
t	time (s)
$w_j(z)$	average vertical velocity of the jet flow ($m\ s^{-1}$)
z	vertical coordinate (m)
z_v	virtual origin height correction (m)

Dimensionless parameters

Fr_x	Froude number for the opening x (–)
R	opening area ratio $\left(=\frac{a_T}{a_B}\right)$
$\hat{z}_v$	dimensionless virtual origin height correction $\left(=\frac{z_v}{h_l(0)}\right)$
λ_x	initial Richardson number through the opening $\left(=\frac{\sqrt{a_x}}{h_l(0)}\right)$
ξ_0	fractional initial dense layer depth $\left(=\frac{h_l(0)}{H}\right)$

Greek symbols

α_{jet}	empirical Gaussian constant for jet velocity profile (–)
α_t	empirical top-hat constant for jet velocity profile (–)
β_{jet}	empirical Gaussian constant for jet radius profile (–)
β_t	empirical top-hat constant for jet radius profile (–)
Δ	magnitude of the difference (–)
ρ	density ($kg\ m^{-3}$)
ϕ	porosity percentage (–)

Subscripts

a	ambient fresh layer
B	bottom opening
E	emptying the whole box
ex	experimental result
l	dense brine layer
m	mixed layer
T	top opening
th	theoretical prediction

Coffey and Hunt [6] classified the flow field of the Emptying-box problem into four flow types according to Froude numbers. The initial top-opening Froude number, at $t = 0$ or $h_l(t) = h_l(0)$, was defined as

$$Fr_T(0) = \sqrt{2}\frac{\alpha_{jet}}{\sqrt{\beta_{jet}}}\frac{\lambda_T}{R}\left(\frac{1}{C_d^2}+\frac{1}{C_d^2R^2}\right)^{-\frac{1}{2}}\left(\frac{1}{\xi_0}-1+\hat{z}_v\right)^{-\frac{3}{2}}, \qquad (1)$$

where $\alpha_{jet} = 7.0$ and $\beta_{jet} = 0.107$ were empirical constants of the turbulent jet flow with the Gaussian velocity profile, C_d was the discharge coefficient, and $\hat{z}_v = z_v/h_l(0) = \lambda_T/(\beta_{jet}\pi^{1/2})$ was the dimensionless virtual origin height correction. The initial bottom-opening Froude number was defined as

$$Fr_B(0) = \sqrt{2}\lambda_B^{-\frac{1}{2}}\left(\frac{1}{C_d^2}+\frac{1}{C_d^2R^2}\right)^{-\frac{1}{2}} = \sqrt{2}\lambda_T^{-\frac{1}{2}}R^{\frac{1}{4}}\left(\frac{1}{C_d^2}+\frac{1}{C_d^2R^2}\right)^{-\frac{1}{2}}. \qquad (2)$$

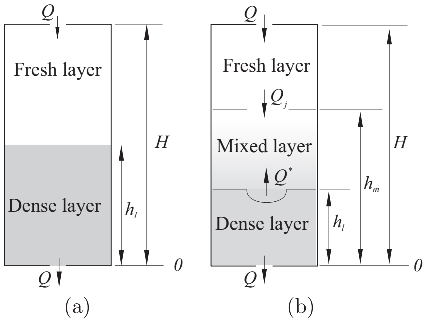

Fig. 1. Sketches of the unidirectional displacement flow patterns of (a) classical displacement flow and (b) displacement flow with interfacial mixing for the Emptying-box problem.

They used the initial top-opening Froude number, $Fr_T(0) = 0.67$, and the initial bottom-opening Froude number, $Fr_B(0) = 0.33$, as two critical values and categorized the four flow types as unidirectional classical Displacement flow, Displacement flow with interfacial mixing, bidirectional Exchange flow, and Exchange flow with interfacial mixing. Coffey and Hunt [6] focused on discussing two unidirectional displacement flow types, as shown in Fig. 1(a) and (b).

Hunt and Coffey [7] further detailed that two Froude numbers at the top and bottom openings were determined by three geometrical parameters, namely the fractional initial dense layer depth, ξ_0, the ratio of the top opening area to the bottom opening area, R, and the characteristic length scale, i.e. a square root of the area, of the top or bottom opening relative to the initial dense layer depth, λ_T or λ_B:

$$\xi_0 = \frac{h_l(0)}{H}, \quad R = \frac{a_T}{a_B}, \quad \lambda_T = \frac{\sqrt{a_T}}{h_l(0)} \quad \text{and} \quad \lambda_B = \frac{\sqrt{a_B}}{h_l(0)}. \qquad (3)$$

This paper focuses on the effect of a baffle of different porosity percentages on the Emptying-box problem, and discusses the connections between two unidirectional displacement flow types by using a baffle of different porosity percentages, which have not been explored in previous research. Two extreme cases presented in Lin and Fan [8], those with and without an impenetrable baffle, are included in this paper to represent two typical flow types, i.e. the unidirectional classical displacement flow and the displacement flow with interfacial mixing. The porous baffle, such as a louver or a mesh screen, plays a role in adjusting the inflow condition to result in a certain effect between two extremes produced by two representative unidirectional displacement flow types. In Section 2, the theoretical models in Refs. [6–8] are used to develop that for the cases with a baffle of different porosity percentages. In Section 3, the experimental setup, experimental series, and the analysis approaches are presented. Experimental results and