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Study of Stably Stratified Flows and Ventilation over Idealized Street Canyons using a Single-Layer Hydraulics Model

Chi-To Ng & Chun-Ho LIU*
Department of Mechanical Engineering
The University of Hong Kong

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*Corresponding Author: Chun-Ho LIU; Department of Mechanical Engineering, 7/F Haking Wong Building, The University of Hong Kong, Pokfulam Road, HONG KONG; Tel: +852 2859 7901; Fax: +852 2858 5415; liuchunho@graduate.hku.hk
Outline

- Background
- Objectives
- Methodology
- Results
- Conclusions
Table 1. Properties of the shallow-water one-layer model in the US standard atmosphere.

<table>
<thead>
<tr>
<th>Thickness of fluid layer H (m)</th>
<th>200</th>
<th>500</th>
<th>1,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air density ( \rho ) (kg m(^{-3}))</td>
<td>1.202</td>
<td>1.167</td>
<td>1.112</td>
</tr>
<tr>
<td>Air temperature ( \theta ) (K)</td>
<td>286.85</td>
<td>284.9</td>
<td>281.650</td>
</tr>
<tr>
<td>Brunt-Väisälä frequency ( N ) (sec(^{-1}))</td>
<td>0.0306</td>
<td>0.0304</td>
<td>0.0301</td>
</tr>
<tr>
<td>Froude number ( Fr )</td>
<td><strong>1.635</strong></td>
<td>0.658</td>
<td>0.332</td>
</tr>
</tbody>
</table>

Remark: It is assumed that the gravitational acceleration \( g = 9.81 \) m sec\(^{-1}\), the fluid velocity \( U = 10 \) m sec\(^{-1}\), ambient fluid density \( \rho_0 = 1.225 \) kg m\(^{-3}\) and \( \theta_0 = 288.15 \) K.

### Buoyancy Frequency

\[
N^2 = -\frac{g}{\rho} \frac{d\rho}{dz}
\]

### Froude number

\[
Fr = \frac{U}{ND}
\]

- Normally known as density stratified flow – density of the fluid varies with vertical position
- Commonly occur in atmosphere and ocean – can be continuous or discontinuous
- The buoyancy force acting on the density stratified flow has dominant effect if sufficient time is given
- Characterize with Buoyancy Frequency \( N \) and Froude Number \( Fr \)
Atmospheric boundary layers can be classified into 3 different types namely:

- **Neutral boundary layer** – Buoyancy effect are negligible
- **Convective boundary layer** – Positive Buoyancy effect, e.g. Day time
- **Stable boundary layer (SBL)** – Negative Buoyancy effect, e.g. Night time

Stull, 1988
Stably Stratified Boundary Layer

- SBL can also be formed by warmer airflow over colder surface, e.g.
  - Warmer air from land flowing over colder water near coastal areas
  - Radiative cooling of the ground surface

- It is important to study SBL because:
  - The boundary layer depth of SBL is much shallower; therefore, concentration of pollutants increases
  - The negative buoyancy destroys eddies generation and therefore weakens mixing and air ventilation performance
  - The trapped pollutants may boost chemical reactions which might become harmful to inhabitants

- Although studies of weakly SBL is well established in various text books and literatures, most fundamental features of strongly SBL remains unknown
• In general, negative buoyancy in SBL suppresses eddies generation, thus negatively affects ventilation performance

• However, hydraulic jump, which occurs in SBL, dissipates excessive kinetic energy into turbulence may enhance both upstream and downstream vertical mixing as well as its ventilation effectiveness

• Hydraulic jump is a sudden transition from critical flow ($Fr > 1$) condition to subcritical flow ($Fr < 1$) condition
Objectives

• Study of ventilation and mixing performance of idealized street canyons under SBL conditions

• Examine the features of high Froude Number flows with simplified SBL conditions by single-layer model

• Determine whether environmental hydraulic jump promotes ventilation performance in urban areas

• Investigate the opportunities for urban planning under SBL conditions
The miniature water channel can easily provide adequate upstream flow velocity (approx. 1.1 m sec\(^{-1}\)) to produce enough \(Fr\) for the hydraulic jump.

\[ Fr = \frac{U}{\sqrt{gH_1}} \]

- \(Fr\) is adjusted by the opening \((H_1)\) of sluice gate and volumetric flow rate \((Q)\).
- Hydraulic jump is induced by the abrupt blockage with height \((h)\).
Methodology

CFD Model - LES

- Code – OpenFOAM 2.1.1
- Large-eddy Simulation (LES) with volume if fluid (VOF) multiphase model

Continuity

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0$$

Momentum

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} \bar{u}_i u_j = -\frac{\Delta P}{\Delta x} \delta_{ij} - \frac{\partial \bar{\pi}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + g'$$

VOF model, $\beta$ denoted the fraction of the fluid phase

$$\frac{\partial \beta}{\partial t} + u_i \frac{\partial \beta}{\partial x_i} = 0$$
Computational Model
- 30 Street canyons
- No. Cells $\approx$ 7 million “prism”
- $y^+ \approx 10$
- Reynolds number $\approx 10,000$

Boundary Conditions
- Grey areas are non-slip walls
- Front and Back are cyclic
- Inlet is bulk velocity inlet
- Top and outlet with total pressure = 0
Results

Observations from Miniature Water Channel

• The quasi-equilibrium state of hydraulic jump will take some time to establish

• Location of the toe of the jump depends on upstream Froude number \((Fr_u)\)

• There exist a critical Froude number \((Fr_c)\) that the hydraulic jump will transit from a standing hydraulic jump to high \(Fr\) jump

\[
Fr_u < Fr_c \quad \text{and} \quad Fr_u > Fr_c
\]
The critical $Fr_c$ was found to be around 2.4 for computational domain with $\frac{h}{H_1} = 0.5$.

- For $Fr < Fr_c$, the toe of the jump will move towards the upstream side.
- For $Fr > Fr_c$, the jump transit into high Froude number jump.

![Image of LESs at different Fr values](image-url)
Results

LES Simulations

- Hydraulic jumps were successfully simulated with the following settings

<table>
<thead>
<tr>
<th>$h/H_1$</th>
<th>0.25</th>
<th>0.5</th>
<th>0.8</th>
<th>1</th>
<th>1.6</th>
<th>2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Fr$</td>
<td>1.7</td>
<td>2.4</td>
<td>2.8</td>
<td>3.1</td>
<td>4.0</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Fr = 1.7
Fr = 2.4
Fr = 2.8
Fr = 3.1
Fr = 4.0
Fr = 4.6
Verification and Validation

- Both the water channel and CFD results were compared with the empirical formula (Forster, 1949)
Results

Velocity profiles and Ventilation performance

- The fluid flow velocity profiles of CFD model with $\frac{h}{H_1} = 0.5$ were examined.
- Profiles were separated into Section A (Upstream) and Section B (Downstream).
- The ventilation performance is measured aloft the street canyons with a parameter $ACH$ (Liu et al., 2015)

$$ACH = \overline{ACH} + ACH' = \int \bar{w}_+|_{\text{roof}} \, dx + \int w'_+|_{\text{roof}} \, dx$$
Flow profile – Upstream (Section A)

- Velocity is normalized by the critical velocity ($U_c$) which corresponding to $Fr = 1$
Results

Flow profile – Downstream (Section B)
Results

Ventilation performance over street canyons (Section C)

- Compared the two different ventilation mechanism
  \[ Fr = 2.4 \text{ (hydraulic jump) and } Fr = 2.8 \text{ (high Froude number jump) } \]
Conclusions

• The single layer hydraulic model tends to over simplify the interactions happening in SBL; however, it provides some useful information and easy analysis with traditional theories.

• Different in Froude number substantially modify the ventilation mechanism over the idealized street canyons under SBL, which may indicate that there is an opportunity for urban planning improvement.

• The CFD results indicate that the boundary height and building height have major effects on the flow mechanism.
Thank you!

Q&A