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

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Outline

- Background
- Objectives
- Methodology
- Results
- Conclusions
Stability of Atmospheric Boundary Layer

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>1.635</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

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

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
Background

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.

\(Fr\) 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 \((h)\).

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

CFD Model - LES

• Code – OpenFOAM 2.1.1

• Large-eddy Simulation (LES) with volume of fluid (VOF) multiphase model

Continuity

\[ \frac{\partial \bar{u}_i}{\partial x_i} = 0 \]

Momentum

\[ \frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j} \left( \bar{u}_i u_j \right) = -\frac{\Delta P}{\Delta x} \delta_{ij} - \frac{\partial \bar{\pi}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} + g' \]

VOF model, \( \beta \) denoted the fraction of the fluid phase

\[ \frac{\partial \beta}{\partial t} + u_i \frac{\partial \beta}{\partial x_i} = 0 \]
Methodology

Computational Domains

Computational Model
- 30 Street canyons
- No. Cells ≈ 7 million “prism”
- $y^+ ≈ 10$
- Reynolds number ≈ 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 exists a critical Froude number ($Fr_c$) that the hydraulic jump will transit from a standing hydraulic jump to high $Fr$ jump.

\[
Fr_u < Fr_c \quad \text{and} \quad Fr_u > Fr_c
\]
Results

- The critical $F_r_c$ was found to be around 2.4 for computational domain with $\frac{h}{H_1} = 0.5$
- For $F_r < F_r_c$, the toe of the jump will move towards the upstream side
- For $F_r > F_r_c$, the jump transit into high Froude number jump

$F_r = 2.4$

$F_r = 2.2$

$F_r = 2.6$
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)

$$ACH = \overline{ACH} + ACH' = \int \bar{w}_+ |_{roof} dx + \int w'_+ |_{roof} dx$$
Results

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 mechanisms
  \( Fr = 2.4 \) (hydraulic jump) and \( Fr = 2.8 \) (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