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Inner Waves Characteristics in a Stratified Ventilated Environment (The Effect of Momentum Jet)

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Abstract

An experimental work was carried out to investigate the effect of inner waves on the stability of flow characteristics in ventilated space. Theoretical and experimental techniques were presented. Energy dissipation by waves and its effect on the performance of ventilation was considered. Analysis of engineering systems in the bases of the internal waves and thermal concept was considered to find out the best ventilation process. The mixing process was investigated experimentally using a turbulent round jet impinged from the ceiling on the inner wave's zone. It was carried out at a flow Reynolds number of $7,000 < Re < 30,000$ and a flow Richardson number of $0 < Ri < 200$ based on the local jet scales. In the mixing process a hot and cold air are introduced to a confined space, to mix in the ventilated space to break down the waves. The results showed that the amount of momentum needed is depending on the wave's amplitude, frequency and flow conditions. It can be seen that the jet momentum has significant influence on breaking down the inner waves and mixing the flow.

Keywords: inner waves, stability, ventilated space, Energy dissipation

1. Introduction

Comfort air conditioning systems provides occupants with a comfortable and healthy indoor environment. It is very important to many workers to related factors that affect their productivity and the satisfaction. Mixing ventilation is where air is supplied into the space with relatively high momentum flux, in order that, the air in the space will be mixed to a reasonably uniform temperature, yet satisfying the requirement for human comfort. In ventilated environment, internal waves are formed at the interface of a stratified air, where air is divided into layers of different temperatures thus into different densities. The lowest layer is made up of cold air, and the top layer is made of warmer air. When the stratified layer flow forward, waves develop between the layers, called internal waves; these waves affect flow currents, temperatures, and human comfort .In oceans the principal sources of internal waves is the atmospheric disturbance of the ocean's upper mixed layer by the wind (Hunger, 1993). During this process, internal waves are emitted, mainly at frequencies close to the inertial frequency, these waves are called near-inertial waves. In ventilated spaces internal waves is dominated by flow currents and thermal stratification, which is very common in buildings were warm air rises under the influence of buoyancy forces, which cause a positive temperature gradient between the floor and the ceiling. Activities such as heating, cooking and welding act as additional heat sources and contribute to already existing temperature gradients across the space.(Turnuer, 1976) Suggested that the stability of a stratified flow is governed by dimensionless parameter K. For laminar flow, the onset of instability indicated by the appearance of waves on the interface occurs at a value of K approximately of 500. For turbulent flow, it occurs at a K value of 180 as mentioned by (Bahnfleth et al., 2003). There are many experimentalists and theoreticians investigated the effect of jets on the flow characteristics in ventilated environment, (Mundt, 1995; Kuesters and Woods, 2012; Kong and Yu, 2008; Cheng et al., 2013; Calay et al., 2000; Said et al., 1996; Awad et al., 2008; Chen, 2000). Mundt (1995) studied both temperature and contaminant profiles in ventilated room. The results showed that the contaminants have been concentrated somewhere in the middle of the room, where the source of heat was located and the higher temperature gradient was evaluated. A comparison of winter heating demand using a distributed and a point source of heating in the case of constant mixing ventilation were predicted by (Kuesters and Woods, 2012)They demonstrated that strong two layer stratification was developed in the space, whereas with low ventilation flux or large heat supply the stratification is weak. With mixing ventilation, the temperature is maintained at the comfort temperature throughout in the occupied zone near the floor of the space.

Numerical prediction on temperature stratification in a room with under floor air distribution system was utilized by Kong and Yu (2008). The different supply air conditions and heat loads were discussed. The results showed that the effect of three parameters, heat load, supply volume flux and supply air velocity, on room air temperature were expressed by the length scale of the floor supply jet. Cheng et al., (2013) Showed that the thermal stratification reduces the heat transfer rate from vertical surface. They also found that the non-Darcian and thermal dispersion effects have significant influences on velocity and temperature profiles as well as the local heat transfer rate. Calay et al., (2000) reported the similarity between stratification in buildings and ones observed in the atmosphere and in lakes and its influence on flow; they recommended the further work to the basic properties of the stratified flow in the maintaining of the internal waves. Stratification in air conditioned space would lead to the formation of a shear layer that affects the effectiveness of HVAC systems. Said et al., (1996) presented the predicted impact of thermal stratification on heating energy requirements. Measured stratification, expressed by floor-to-ceiling temperature differential, was in the range 4–11 °C. Two air layers existed in the confined space, a warm upper air layer and a cooler lower air layer with a significant impact on the building's heating energy requirements.

Awad et al., (2008) studied the phenomenon of stratification in the built environment, and evaluated the stratified flow characteristics such as stratified layer thickness, stratified layer interface level height and the degree of stratification as a function of flow parameters; he applied the concept of jet momentum on the inlet airflow and studied its effect on stratification in the built environment. Chen (2000) showed that the thermal stratification reduces the heat transfer rate from vertical surface. They also found that the non-Darcian and thermal dispersion effects have significant influences on velocity and temperature profiles as well as the local heat transfer rate. Awad et al., (2008) studied the effect of flow parameters such as airflow rates, opening heights, and flow direction on the stratified flow characteristics. Also they studied the effect of momentum jet on mixing the stratified flow using a recently available experimental technique. Smoke visualization was used to validate the experimental work and to indicate the effect of air jet flow on the stratified flow characteristics. The purposes of this part of work were to investigate experimentally the effect of both Reynolds number and Richardson number on the mixing processes, and the effect of momentum in breaking down the inner waves using turbulent round jet with different possibilities of flow injected by ceiling jet supplies (Said et al., 1996).

2. Experimental Apparatus

The experimental set-up used to support these models was presented. The flow parameters such as; input airflow, temperature, openings heights and other parameters were used to model the flow patterns transactions. All tests were conducted in the test environmental chamber at the University of Hertfordshire as presented in Figure (1). The physical dimensions of the chamber were large enough, so that the walls didn't affect the flow, and the height was Sufficient to the buildup of stratified layer. The dimensions of the identical rectangular chamber were (7.5m long, 3.6m wide and 3.0m height) with two windows (double glazed) isolated from an enclosed space. The walls of the test chamber were insulated. The walls as well as the roof were of 12.5 cm thick, with white polyester outer finish and polyurethane foam interior made. The floor was a layer of light grey color of 10 cm thick concrete, and below it a layer of 10 cm thick Styrofoam. Transient temperature distributions for the flow inside the chamber were measured using eighteen K-type thermocouples. The thermocouples stand was inserted vertically on a multidirectional movable base located at the centre of the chamber. The experimental methodology has permitted us to obtain complete descriptions for the boundary conditions (supply air temperature and flow rate, inside temperatures and chamber boundaries), and all measurements were made under steady-state conditions. The experimental data must give the indication of the wave's characteristics such as the amplitude and frequency, and to predict the best conditions of flow to be used in designs and applications of ventilation systems. Also to study the effect of layers overturns on inner waves, and to study the time needed to break down the waves as time scale affects flow energy.

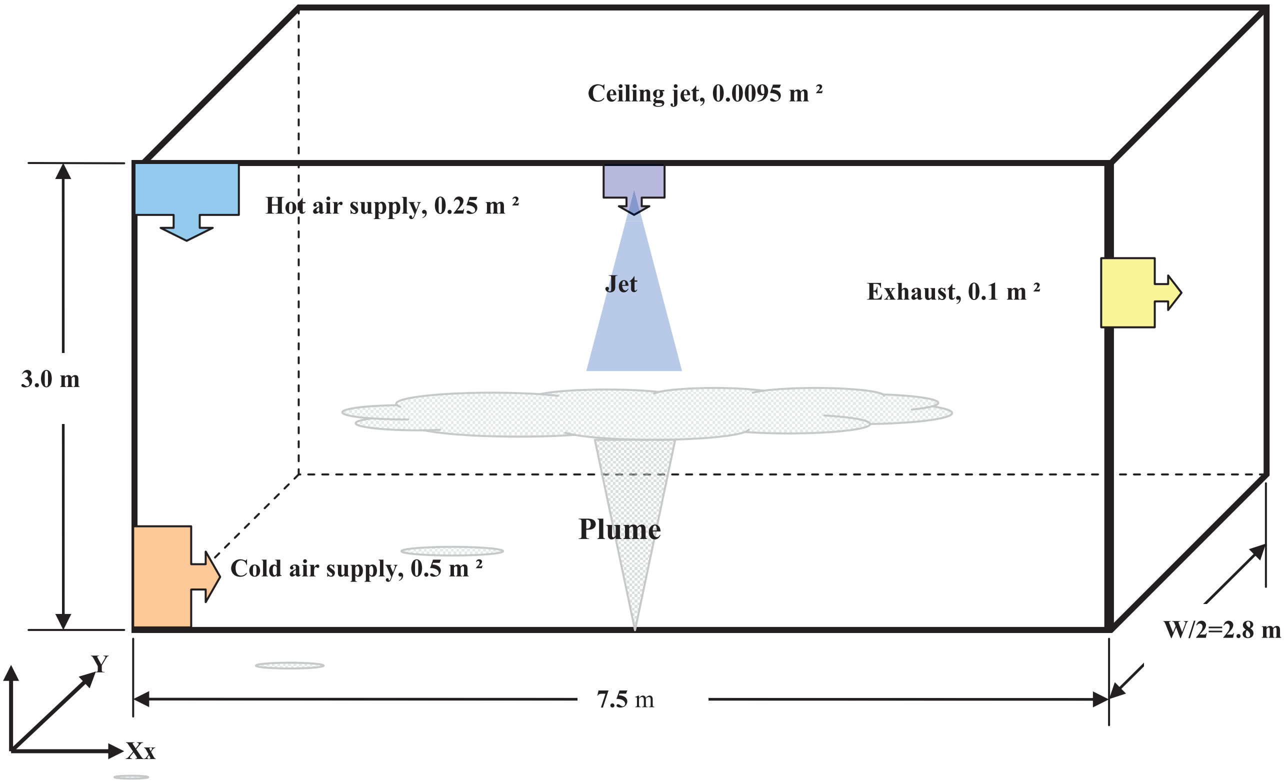

Figure. 1 Definition sketch of the environmental chamber showing a diagrammatic representation of the input airflow supplies, exhaust, and ceiling jet (Awad, 2005)

3. Theoretical Analysis

For finding the potential and kinetic energy dissipated by the waves, a schematic description shown in Figure (2) is considered (Website).Consider the work done in deforming the interface between fluids 1 and 2. In case A, fluid 2 is lifted up to displace fluid 1, in case B, fluid 1 has been pushed down to displace fluid 2, integrating the work over half the wavelength and doubling it because of symmetry gives (Website)

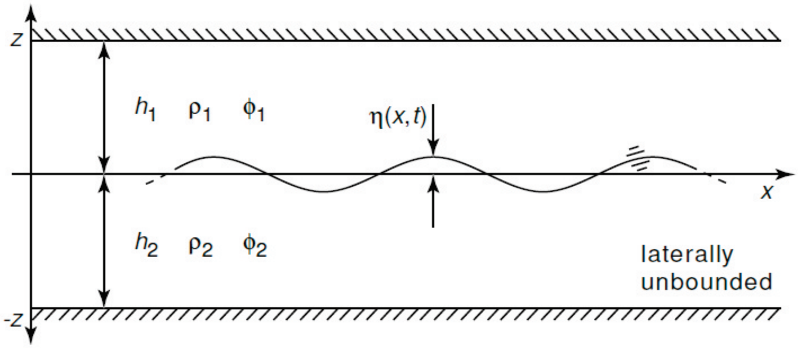

Figure. 2 Schematic description of the system

$$E_P = \frac{g(\rho_2 - \rho_1)}{\lambda} \int_0^{0.5\lambda} \eta^2 .dx \tag{1}$$

It can be verified that the potential energy is given by

$$\mathrm{E_P} = \frac{1}{4}(\rho_2 - \rho_1)\,\mathrm{g}\,\mathrm{A}^2 \tag{2}$$

The kinetic energy is given by,

$$\mathrm{E_k} = \frac{1}{4}(\rho_2 - \rho_1)\,\mathrm{g}\,\mathrm{A}^2 \tag{3}$$

The equations (2) and (3) are used to find the total energy, which is given by:

$$\mathrm{E} = \frac{1}{2}(\rho_2 - \rho_1)\,\mathrm{g}\,\mathrm{A}^2 \tag{4}$$

or

$$\mathrm{E} = \frac{1}{2}\left(1 - \frac{\mathrm{T_2}}{\mathrm{T_1}}\right)\rho_o\,\mathrm{g}\,\mathrm{A}^2 \tag{5}$$

Compare this result to that for surface waves:

$$\mathrm{E} = \frac{1}{2}\rho_o\,\mathrm{g}\,\mathrm{A}^2 \tag{6}$$

$$\frac{\mathrm{E_{surface\,waves}}}{\mathrm{E_{innerwaves}}} = \frac{\rho}{(\rho_2 - \rho_1)} \tag{7}$$

In ventilated spaces the difference in density is comparatively small, so the right hand side of equation (6) is much greater than one, which led to the conclusion that the energy of surface waves is greater than the energy of internal waves, then for any given energy, internal waves will have much larger amplitude than surface waves. Is the inverse of Richardson number and it represents the flow speed over the free surface wave speed. In internal waves, Froude number is convenient for shallow waves, so it carries an important part in the analysis of engineering application associated with internal waves

.

$$F_D = \frac{u}{\sqrt{g' L}} \tag{8}$$

Where $\mathbf{g' = g\frac{\Delta\rho}{\rho}}$, and defined as the reduced gravity, and L is the characteristic length.Stratification is most likely to occur at low flow velocities; Richardson number gives a qualitative method to determine the effect of velocity on mixing of the fluid thus on stratification:

$$\mathrm{Ri} = \frac{\mathrm{g}\,\Delta\rho\,\mathrm{d}}{\rho \mathrm{u}^2} \tag{9}$$

d: is the characteristic length.

If the density gradient is large relative to velocity gradient, stratification would occur. If density gradient is small relative to velocity gradient, mixing would occur and no stratification. The stability parameter K, as suggested by (Turnuer, 1973)) is given by:

$$K = \frac{Re}{Ri} = \frac{u^3}{\nu g} \tag{10}$$

For laminar flow, it is approximately to 500. For turbulent flow, the instability occurs at a K value of 180 as mentioned by (Bahnfleth et al., 2003).

4. Results and discussion

The variations of vertical temperature profiles for long period of time (72 minutes) are shown in Figure (3). Every single profile from this sequence is only representative of the vertical potential temperature profiles at the given time. It shows the temperature variations inside, beside and outside the wave region. From the results, we have seen that a steady temperature profile is existed outside the wave zone. The flow is steady, uniform and fully mixed, where the time and vertical temperature gradients are ($dT/dt \approx 0$ and $dT/dz \approx 0$). The formation of steady uniform flow shown outside the wave zone in Fig. 1 is due to high buoyancy forces so high Richardson number and high stability. In this region the velocity is comparatively low, the Reynolds number is so low and the flow is laminar. The temperature profile close to the wave zone shows small fluctuations that resulted from velocity disturbances and forced convection heat transfer by the waves.

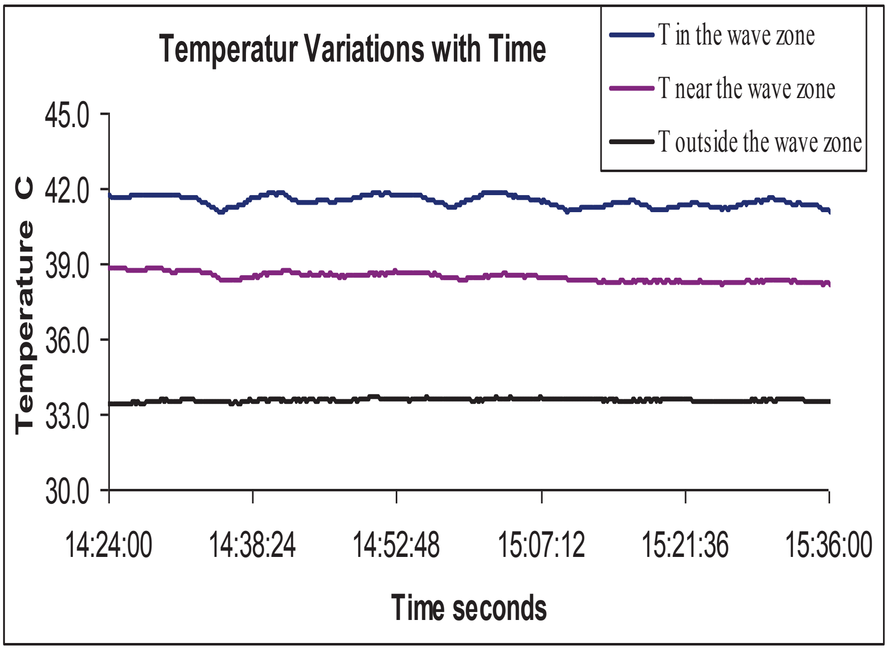

Figure. 3: Temperature distribution across the chamber at a fixed axial location of (3.75, 2.8) m in the environmental chamber.

For this region, the temperature is semi steady and the flow is non-uniform, where the time and vertical temperature gradients are ($dT/dt \approx 0$ and $dT/dz \succ 0$). The temperature profile inside the wave zone shows a fluctuation with time, it is due to comparatively high momentum, so low Richardson number and low stability with time. In this zone the velocity is comparatively high, the Reynolds number is so high and the flow is Turbulent. In this zone, a dynamical significance full-scale inner waves was formed with (z=1.25 m, A=0.3 m and ($dT/dz = 8\ ^{\circ}C/m$). Both vertical temperature profiles above and below the wave zone was quite linear $dT/dz \approx 0\ ^{\circ}C/m$

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Figure (4) shows how the momentum influences the wave's amplitude A. In this case, the injected air will flow through the interface and mix the flow depending on the amount of momentum. More increase in jet momentum will break down the waves leading to fully mixed environment. The results reveal the effect of momentum on the flow temperature profiles. The temperature profiles indicated the decrease in the temperature difference and wave's amplitude. It shows how the wave's amplitudes change with the change in momentum. At the start, the variations is significant, it decreases steadily until it reaches the minimum. It is due to the significant increase of inertia forces compared with the buoyancy forces (the Richardson number Ri). The effect of both Reynolds number and Richardson number on the mixing processes was investigated experimentally using air modeling technique. A turbulent round jet impinged from above on the inner wave's zone over a flow Reynolds number of 7,000< Re <30,000 and a flow Richardson number of 0< Ri< 200 based on the local jet scales was used. The effect of Richardson number on the wave's characteristics is shown by Figure (5). The results show the change in the wave's amplitudes A with the flow Richardson number Ri. The value of Ri was varied between 4 to 200, which are very much spans over a wide range of operating conditions. The results show the effect of Ri number on the wave's amplitude A. As the Ri increases, the wave's amplitude is gradually increases due to the increase in the ratio of buoyancy forces related to the momentum forces. For high values of Ri = 200, the waves amplitude A is shown to be with significant effect leading to a strong waves in the environment. As the value Ri decreases to 4, A is decreased. Above this zone a high average temperature is expected to form in the upper zone, upon further human discomfort will occurred The variation of wave's amplitude with the Reynolds number is displayed in Figure (6). The Reynolds number was varied between 7000 and 30000. The results show significant variations in the wave's characteristics due to the increase in momentum forces upon the increase in Reynolds number. Weak inner waves are shown to form with the increase in Re values. With further increase in jet speed, so Re, waves start to decay and break down, the temperature of the air becomes uniform, ventilation efficiency will increase and the human comfort will occurred. The results reveal the effect of momentum on the wave's characteristics.

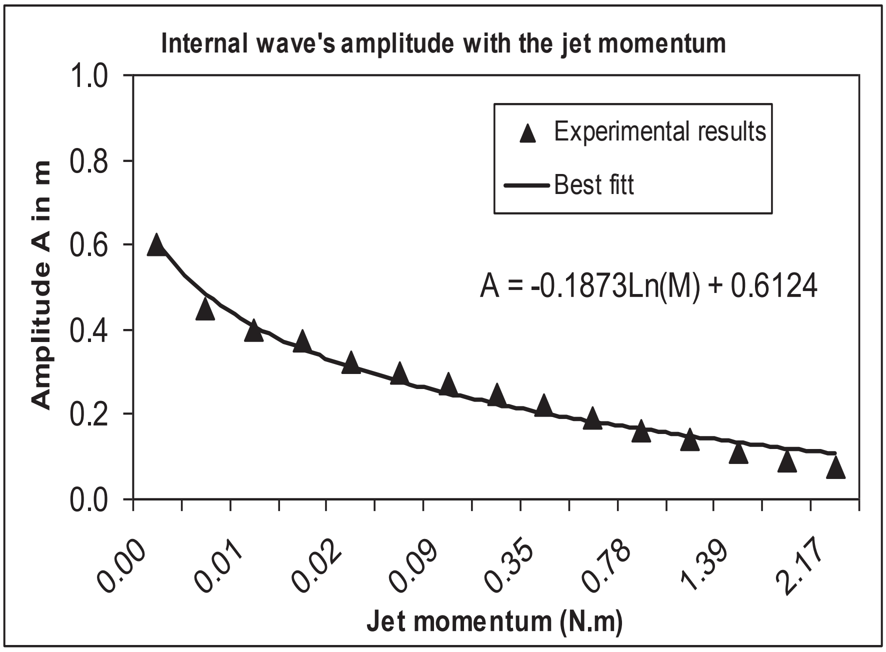

Figure. 4: Variations of the wave's amplitude 2A with the jet momentum for various values of airflow rate.

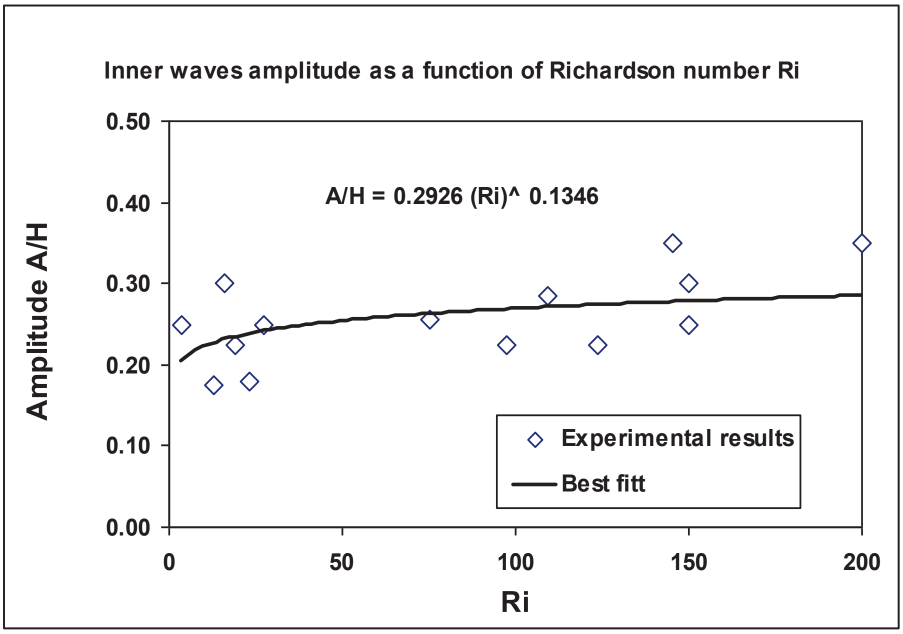

Figure. 5: Variations of the wave's Amplitude 2A/H with the flow Ri number for various values of airflow rate.

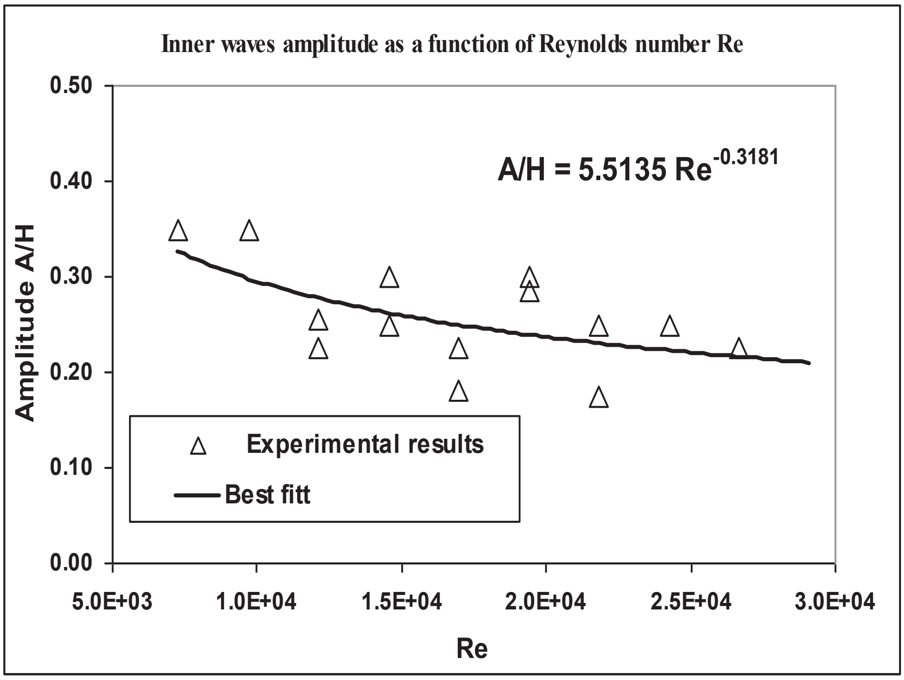

Figure. 6: Variations of the wave's Amplitude A/H with the flow Re number for various values of airflow rate.

As the jet momentum increases, the wave's amplitude is gradually decreases, which is due to the circulation of flow in the wave's zone, which generates a shearing force through the space. This will tear out the wave's zone, and increase mixing in the flow. Comparing the results in Figur (5) with those in Figure (6), it can be noted that, the effect of Richardson number is at the opposite of Reynolds number .While Ri propagate the flow to stratify and the waves to form, Re resulted in a high momentum make the layer to become thicker and the mixing in the wave's zone becomes higher and faster. It tears the waves or destroys it depending on the momentum and the wave's potential.

Figure (7) shows the variations of wave's amplitude with Archimedes number Ar since it characterized the amount of buoyancy forces. The value of Ar was varied from 0.0 to 70. The low values of Ar indicate the low values of wave's characteristics where the buoyancy forces become diluted, while the momentum forces become concentrated. With more increase in Ar, the flow becomes further stratified, the wave's amplitude becomes higher and the waves become thicker and stronger. Comparing the results in Figure (6)with those in Figure (7) , it can be concluded that, the effect of buoyancy forces is at the opposite of momentum forces. While the effect of Ar on the waves characteristic A/H is small, the effect of Re is higher. Thus the effect of Momentum forces on the wave's characteristics is greater than the effect of Buoyancy forces.

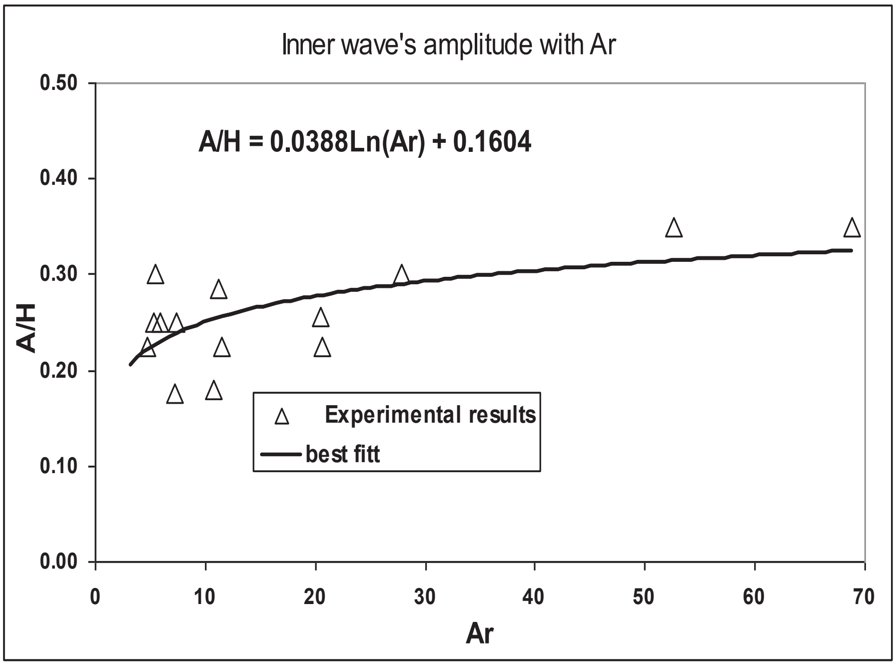

Figure. 7: Variations of the wave's Amplitude A/H with Archimedes Number for various values of airflow rate.

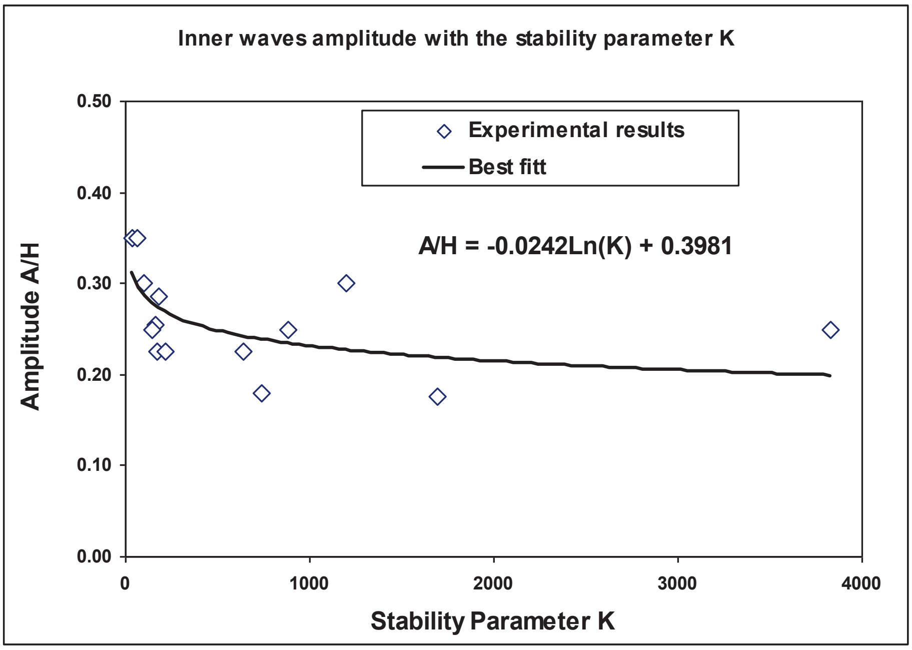

Figure. 8: Variations of the wave's Amplitude A/H with the Stability Parameter K for various values of airflow rate.

Figure (8) shows the variations of the amplitude A/H with the stability parameter K, for various values of flow rates. The descending variations during the flow (Re= 7,000 to 30,000, Ri= 3 to 200), decreases slightly with K before converging towards the steady case and thus forming mixed flow, regardless of the higher values of K. In this case the inner wave's amplitude is approximately constant and not affected by K, so it is not found to depend on K either. Furthermore, the mixing will be higher and faster. On the other hand, at small values of K, the descending variations are too high, which result in a significant decrease in the wave's amplitude. In this case, the wave's amplitude A/H is comparatively high and the stability parameter K is comparatively low. Smoke visualizations are included for comparison with the experimental results. The experimental and visualization results obtained in this work are in good agreement considering the different modeling technique and flow conditions. Comparisons illustrate the effect of momentum on the wave's characteristics. As the momentum is so low, the smoke image indicates a more stratified flow, and waves were form in the wave's zone. As the momentum is so high, the smoke image indicates a more mixed flow in the wave's zone, which is so important to design ventilation systems considering the pollutants to be above the heads of people in the working zone.

5. Conclusions

The effect of momentum jet airflow on the internal wave's characteristics was investigated by using experimental techniques and smoke visualization. The jet momentum has significant influence on the mixing of the flow and the wave's characteristics. The results indicated that once the momentum was initiated a mixed flow grew in the occupied zone above the floor. The results showed that the wave's amplitude is a function of the initial jet momentum over a wide range of flow rates, despite of different types and values of jet flow. It was inversely proportional to the momentum. Also it is seen that increasing the momentum will decrease the wave's amplitude height, and more increase in jet momentum will increase the mixing in the wave's zone and destroy the inner waves. However, the significant effect of Reynolds number to Richardson number, indicated by the instability parameter K, was inversely proportional. From the comparisons, it is seen that the mixing is higher and faster in case of high values of K since the temperature gradient and the wave's characteristics were not strong enough.

Nomenclature

A	Amplitude (m)
Ar	Archimedes Number
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E	Energy (W)
g	Gravity acceleration (m/ s^2)
g'	Reduced gravity (m/ s^2)
H	Height (m)
Q	Volume flow rate ($m^3/\min$)
K	Instability dimensionless parameter
R	Universal gas constant (kJ /kg ˚K)
Re	Reynolds number
Ri	Richardson number
T	Temperature (˚C)
ΔT	Temperature difference
u	Velocity
x, y, z	Horizontal, transversal and vertical coordinates.

Greek symbols

η	Fluid interface position (m).
λ	Waves length (m)
Δ	Difference between variables.
ν	Kinematics viscosity ($m^2 \cdot s^{-1}$)
μ	Dynamic viscosity (kg/m s)
ρ	Density (kg/m)

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