Experimental study on augmentation of mixing within a stratified indoor environment by erosion of density interface.

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Abstract. The current study aims to address the problem associated with warm air heating in passive houses. Warm air eating is cheaper and easy to operate in passive houses, however, this creates problems of shortcut ventilation and thermal discomfort due to stratification as warm air is confined to the ceiling. In the current study, we explore a new method of creating resonance between stratification frequency and the periodic variation of the ventilation supply frequency to increase mixing of the supplied warm air and the room air consequently destratifying the room conditions. A basic water model study is used to understand the interaction between the frequency variations and the resulting standing waves with stratification characteristics in a room. Measurements at three different input frequencies and at three input paddle locations have been performed, gathering vertical temperature gradients and visualization data from them. The results show the shift in the inversion point because of an increase augmentation across the inversion between the fluids with different densities close to resonance. There is also a dependency on paddle location showing that the type of ventilation system will have different mixing rates due to different fluid energetic behaviours.

1 Introduction

Passive houses or Low energy houses (LEHs) are designed with building technologies that reduce the energy use and optimise on local resources. LEHs normally use warm-air heating systems which incorporate heat recovery ventilators within the mechanical ventilation system to cover the space heating demand [1]. This reduces the heating demand considerably since the ventilation system recovers heat from the exhaust air to preheat the supply air thus returning the heat back into the house. The heated supply air is provided through supply diffusers which are located at ceiling level together with exhaust air terminals. The consequence of this setup is that the heated air has difficulties to penetrate the occupied zone due to stratification, resulting in an ineffective ventilation due to uptake of newly supplied air back into the exhaust (short circuiting ventilation) and thermal discomfort as warm air is confined to the ceiling instead evenly spread in the occupied zone. Thus, thermal comfort and poor indoor air quality are among the major complaints on passive houses [2–4]. There is a need to develop new methods for distributing heated ventilation air that is both efficient and provides accepted thermal comfort to occupants. Achieving this goal is a prerequisite for a widespread acceptance of passive houses which will lead to a permanent reduction in energy use.

Stratified indoor environments are characterized by a range of spatial and temporal scales, of which processes like internal waves, turbulence instability and diffusion among the few, play an important role in the vertical spread of heat, moisture, momentum, and indoor contaminants in the building. The same characteristics happen at a large scale in oceanography and meteorology [5], thus we can apply similar approaches to get basic understand of stratified indoor environments and develop methods to augment mixing. For example, Osborne and Cox [6] looked at fine scale temperature structures in which intensity of destratification was created by the variance of the temperature gradient due to mixing events. According to Park et al, [5], Gibson [7–10] proposed a model of energetic mixing events that create packets of mixed fluid that then interleave with surrounding fluid. Later, Park et al applied these concepts to understand density structures, fluid interfaces and layers by stirring a fluid uniformly to create unsteady conditions.

Current studies in ventilation have explored the effect of unsteady ventilation systems on indoor environmental conditions and occupants' thermal comfort [11]. For example, periodic variation of supply of isothermal air results in better mixing which in turn leads to better ventilation and comfort [12,13]. Warm air supply generates a stratified flow within the room that has an internal frequency (Brunt-Väisäla frequency or buoyancy frequency defined as a measure of the stability of a fluid when exposed to displacements). Our idea is to supply warm ventilation air as a time periodic flow with a frequency around a steady mean flow. The aim of this study is to develop a basic understanding and systematically explore the influence of periodic variations of warm air supply and its interaction with stratification characteristics in a room. We can then apply this understanding to develop strategies to overcome challenges of stratification in energy efficient houses with warm-air heating. For example, what operation supply frequencies should be considered, what are the appropriate position of the supply terminal and how do room and operational parameters influence performance? This project is a pilot study and aims to investigate and give insights, as a first step, on the potential of the proposed new method and identify the

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resonance frequency and how it is influenced by room characteristics (temperature, ceiling height, and volume etc.)

2 Method

In the current study, a preliminary investigation with a small-scale water model working was carried out. The approach was to create a stratified profile in the water tank and introduce disturbances through linear movements of a paddle consequently creating standing waves that interact and create mixing on stratified fluid layers, similar to earlier investigations [14] on displacement ventilation. The studies were performed at the multipurpose laboratory at the University the University of Gävle in Sweden.

2.1 Apparatus and procedure

A setup of a 0.24 m x 0.24 m x 0.24 m Plexiglas tank, filled with tap water up to a height of 0.20 m, and integrated with an 80 W electric heater was immersed at the height of about 11 cm and a thermocouple measurement rig was used, see Figure 1(same thermocouple rig used in our earlier study [15]). The water was heated until there was a 15 °C temperature difference between lower and upper thermocouples on the measurement rig, shown in Figure 1B. After which the heater was removed and a 5-minute dwelling interval was used to attain quasi-steady state conditions in the tank, then the paddle (size: length of 0.12 m and a height of 0.06 m) was switched on to introduce mixing. The paddle was driven by a stepper motor through computer programme and moved back and forth. One back and forth motion was defined as an excursion, and the length of one excursion was 0.01 m in all runs.
The thermocouple measurement rig was made of T-type thermocouples (class 1) with a tip diameter of 0.6 mm and a factory accuracy of ±0.3 ºC. A total of 18 thermocouples spaced 1 cm apart were mounted on an in-house manufactured test rig. The thermocouples were calibrated in the range of 10 – 30 ºC with 2 Hz frequency operation mode at uncertainty of ± 0.1 ºC (calibrations were done with heating air). LabVIEW software was used to monitor and record all measurement data.

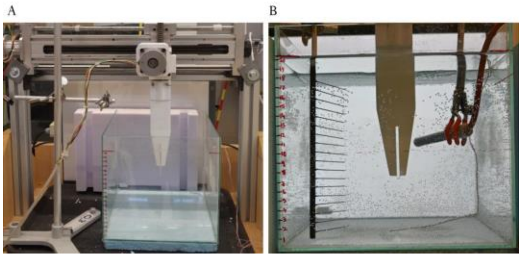

Fig. 1. (A) Water model and paddle assembly: (B) experimental setup.

In addition, qualitative data acquisition (visualisations) was obtained by adding dye to illuminate the desnisty differences, inversion point and mixing effect/rate between layers of different densities.

The important parameters of consideration are the Brunt-Väisäla frequency or buoyancy frequency (N),

$$N = \sqrt{\frac{d\rho}{dz} \cdot \frac{g}{\rho_0}} \tag{1}$$

where,

$$\rho_0 = \rho\left(\frac{T_H + T_C}{2}\right) \tag{2}$$

$$\frac{d\rho}{dz} = \frac{\rho(T_H) - \rho(T_C)}{h} \tag{3}$$

ρ_0 is the reference density dependant on the arithmetic mean of temperature of the liquid at the lowest fluid temperature T_C and the highest fluid temperature T_H. h the vertical distance between the highest and lowest located thermometers and ρ is the density of the fluid.

The Reynolds number of the paddle (Re), and the Richardson number (Ri), defined as

$$Re = \frac{\rho v L}{\mu} \tag{4}$$

$$R_i = \frac{N^2 L^2}{v^2} \tag{5}$$

where the characteristic length L [= $(a+b)/2$] defined by the length a and height b of the paddle, and the fluid has a dynamic viscosity μ and the paddle has a velocity v.

The paddle was operated in three different positions: Above the inversion point (top) across the inversion point (middle) and below the inversion point (bottom). Three paddle frequencies were investigated corresponding to three Reynolds and Richardson numbers. The parameters of the experimental runs are shown in Table 1.

Table 1. Operational parameters.

Paddle v (m/s)	Paddle f (Hz)	N (Hz)	Re	Ri
0.09	1.51	1.45	9382	1.92
0.06	1.02	1.45	6365	4.18
0.04	0.60	1.45	3728	12.18

Note: Every recorded instant provided the temperature of at 18 local thermocouples on the test rig and the initial temperature difference between the highest and lowest point on the rig was measured to calculate Brunt-Väisäla frequency (corresponding to a temperature difference of about 15 ºC). Since there were small differences in measurements between cases, a mean value of 1.45 Hz is used in the analysis.

3 Results and discussion

This section presents the results and discussion of the experimental study. The measurement results are presented as a summary of the obtained temperature profiles to represent stratification tracing with time. Additionally, the visualization of the dissolution of the stratification profile and the corresponding mixing rate with respect to paddle frequency and position were made. Subsequently, behavioural characteristics of the initial inversion point after introducing paddle oscillations followed by a discussion on the implications of the change in potential energy between different fluid layers due to dissolution of stratification boundary conditions.

3.1 Stratification profiles and the mixing rate

Figure 1 shows the evolution of the evolution of the normalized temperature difference as a ration of $(t_p - t_h)/(t_c\text{-}t_h)$, where t_p is the temperature at a rig point, t_h is the highest and t_c the lowest temperature on the measurement rig. This approach is taken as a representation of density distribution in the tank.

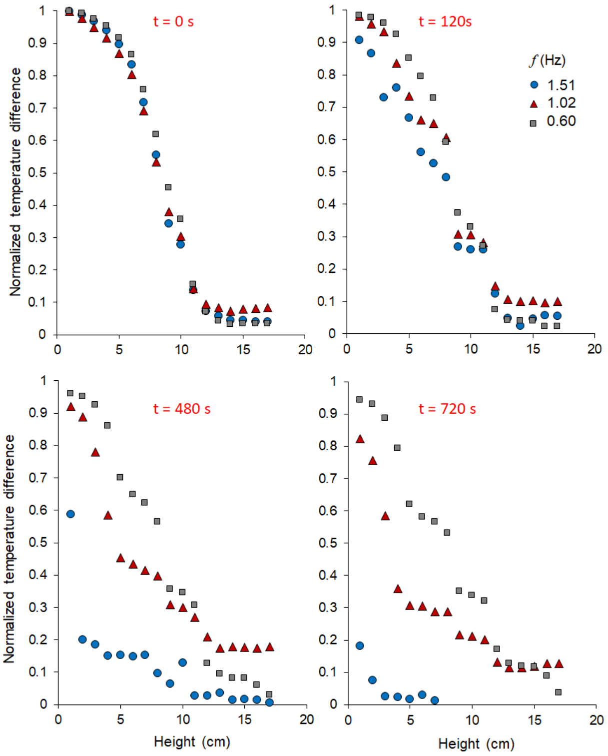

Fig. 2. Normalized temperature profile as a representation of density distribution and its evolution against time.

In Figure 2, the paddle is placed in the middle of the tank or just at the centre of the inversion point (at the height of about 9 cm), the rest of the measurement cases had similar profiles with only differences of dissolution time (as shown in Figure 3). The paddle frequency close to the Brunt-Väisäla frequency had the fastest mixing effect, showing that obtaining resonance between the oscillation and Brunt-Väisäla frequency increases augmentation of mixing in a stratified environment. In addition, the fastest augmentation was when the paddle was in the middle and bottom position. it has been observed that the fastest measurements were the ones taken with the input frequency in the stratification layer level, followed by the bottom ones and finally by the ones with the paddle located at the top of the water model. This means that when inducing mixing at the boundary layer that separates warm input air from existing colder air in a LEH, mixing may be achieved faster, enhancing thermal comfort of the occupants. This fact may be due to breaking the generated turbulence by the stratified medium internal waves right where they are located, without the presence of any other fluid between the input flow and the stratification layer.

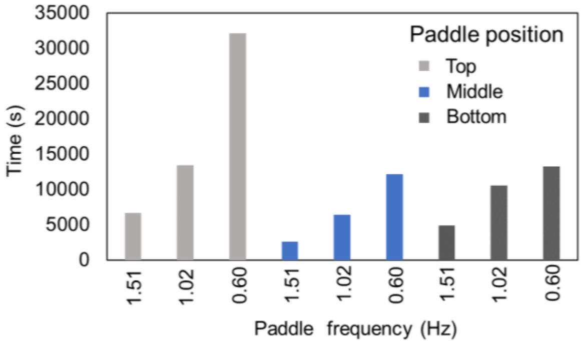

Fig. 3. The mixing time for each respective paddle position and frequency.

3.2 Movement of the inversion point

Figure 4 depicts the movement of the inversion point over time after introducing mixing, in this case a middle-placed puddle at a paddle frequency of 1.5 Hz is represented.

The observations were that the transfer of the stratification inversion layer over time were similar when the paddle was at the top and middle locations. In these positions the mixing effect was transferring the warmer fluid from the top to the lower region. When the paddle is placed at the bottom the region with the cold fluid was eating away the inversion point consequently moving it upwards and the mixing effect between fluid layers was slowly introducing heat transfer from warmer region to the colder region, see Figure 5.

A limitation as seen from the observation is the effect of the paddle on the mixing, under these circumstances there exists an undesired effect on the mixing caused by the intrusiveness of the paddle. However, there is not much that can be done to mitigate this effect more than being aware that the employed paddle differs from the input ventilation system that may be employed with a fluctuating supply ventilation flow in a passive house.

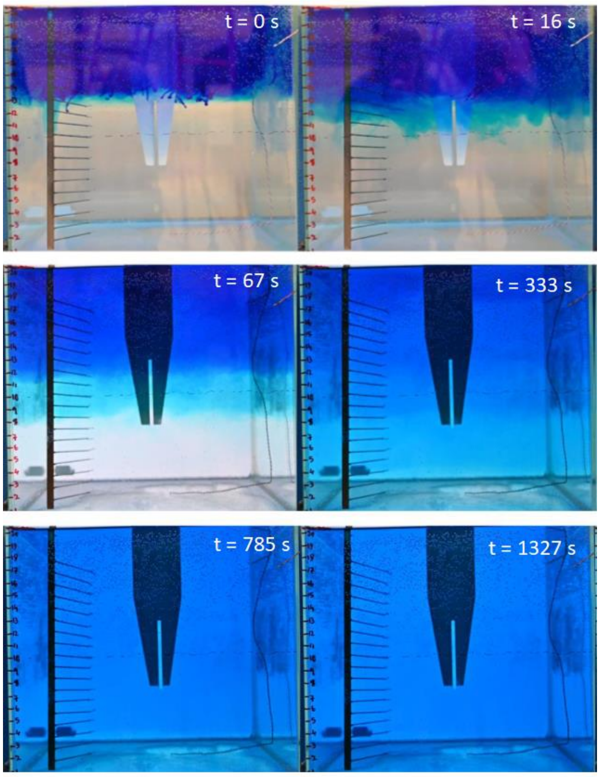

Fig. 4. Visualization at the middle position at paddle frequency 1.5 Hz.

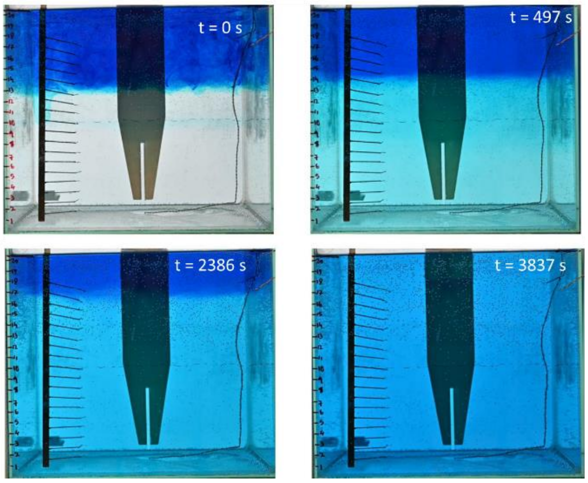

Fig. 5. Visualization at the bottom position at paddle frequency 1.5 Hz.

This was an interesting observation; thus, the evolution of the initial inversion point over time was assessed by plotting the normalized temperature, i.e., local inversion temperature divided by the highest value of their respective function. Figure 6 shows this analysis and as seen, when oscillations are introduced at the bottom of the water model tank, the inversion point initially gets cooled down to later get heated up, presenting a positive slope, which may be caused by the rotary movement of the induced mixing process. There is an existing delay in the temperature decrease at the initial inversion point corresponding to the time it takes in the inversion point to change from being cooled down to be heated up. Note that all three frequencies' plots present similar shapes of the function of the temperature over time. This suggests that the system energetics will differ depending on the location of the disturbances, i.e., the potential energy introduced by stratification will change due to change from the initial vertical density distribution to the constant fluid density after mixing [5].

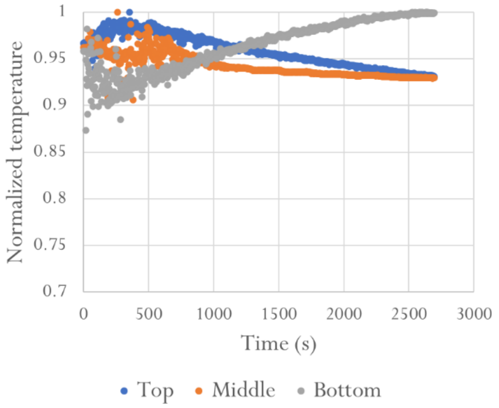

Fig. 6. Evolution of the normalized temperature at the inversion at paddle frequency 1.5 Hz.

4 Conclusions.

The current study shows that time varying mechanical input enhances mixing in stratified fluid environments with the fastest mixing effect occurring when the frequency of the oscillatory variations is in resonance with the Brunt-Väisäla frequency. However, the mixing rate has a dependency on the location of the mechanical input of the oscillations in the stratified environment. This dependency shows that fluid dynamics regarding mixing between fluid layers may differ and energy transfer between layers or regions of different temperatures or densities will also differ. In practice, results and findings from this study shows that the location of the supply with fluctuating flow may have implications on the mixing effect in the stratified environment. The position of the air diffuser that delivers oscillatory air supply or the type of air distribution that is employed (mixing or displacement) can be critical on the mixing rate consequently the system energy use. More studies are needed to critically assess the energy transfer between fluid layers and how to quickly mix the fluid with minimal effect on occupants' perception particularly draft.

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