CHAPTER 2

THEORIES AND LITERATURE REVIEW

This chapter primarily states about theories and literature review which related to important boundary conditions for experiments in next chapter. The content of this chapter are building regulation, weather data, factors of comfort, and standard of comfort zone. This chapter is also pointed out about theories of air movement and heat transfer in Trombe wall system, thus introduced about stack effect strategies embracing previous research studies experiences associated, and finally adding the background of experiment tool, XFlow CFD. To better understand about the topic, these are some important keywords to determine as following.

"Ventilation" is the process of supplying or removing air, by natural or mechanical means, to or from any space; such air may or may not have been conditioned [5, p. 883].

"Row house" or "Row dwelling" is one of an unbroken line of houses sharing one or more sidewalls with its neighbors. Row house is also defined as one of a number of similarly constructed houses in a row; usually in a housing development [5, p. 701].

"Trombe Wall" is one of the passive solar applications adding on stack effect. This system use sun radiation to induce ventilation in an air gap which is proposed a side as building wall and another side is glass.

2.1 Phnom Penh Row houses and regulations

Row houses are desirable for middle class family, while the heads of family are the staffs working for public or private sector, and some own small family business. Usually, the family's members have at least four people who are parents, children, housemate, and their relatives.

Generally, low-rise type of row houses surround Phnom Penh City contain three stories: ground floor, first floor, and second floor. Ground floor area usually have or have no a car park in front, a living room, and a kitchen with the set of dining table. There also common to design for an upper mezzanine floor with two bedrooms above ground floor. Another two bedrooms are on first floor, then the second floor appears only open space for storing water container, dry clothes with a stair block from downstairs. Thus, this topic of thesis would particularly focus on ground floor area as the principal part to improve the ventilation rate among all of the other amenities, since living room and kitchen are the public place for all family members where they spend much of their time to be in.

Figure 2.1 Picture of Phnom Penh row house for the study case

Row house for pilot case shows that the common width of row house in Phnom Penh is between 4 to 5 meters, and about 14 to 20 meters wide. However, the most common designs are 4.2 x 16 meters structure, built on two to three levels that can contain basic amenities. It can accommodate a living room and a kitchen on ground floor. There is also a small bedroom there for the house which has longer length. However, many houses left from 1960s, front part on ground floor functions as “shop house” for family business such as grocery shop, restaurant, café, office and so on. To gain more space, there appears from the 1990s until now the mezzanine floor for row house. This floor is added practically for sleeping area as majority and some are for storage. Nowadays, some houses have twin room on mezzanine, some have one room at the back or front side of the house. First floor consists of one big bedroom and another fair size one. New design shared some space from that big bedroom to make family room. The second floor or top floor normally exists with only stair block area and some roof covered, which provides spare space to store water containers, some used and unused staffs, dry clothes, thus for some family event.

According to Cambodia Construction Law[1], the height of the building is set by the average height differently by districts, type of buildings and site location [6]. Specification to the residential buildings in the city, the height is set by the area of plot, road width, surrounding facilities, the situation of economy, environment, society, culture, geography, health comfort, and aesthetics [7]. For low-rise building, the height can be defined by one of the method below:

1. Elevation height in meter: there are maximum to construct for 2 stories not include ground floor. Floor height must not exceed 5meters per floor.
2. Floor area and plot ratio: for low-rise attached-house, total floor area must not exceed 1.5 times to the plot area.
3. Proportion of road width and building height: this is implemented for the buildings along the road width not exceed than 9 meters. The ratio of the building height to the road width plus the side-walk must not exceed 1:1.

In this pilot case study, the principle number 1 is followed. Each floor is not exceed than 5m even if the mezzanine floor is added. About article number 2 and 3, it is depend on location of houses which is difficult to make a common conclusion. Since there will be a little bit changes only at the top floor by adding Trombe wall system, the new design will not affect to the height of the house.

[1] Cambodian Government, Construction laws, 1997, Article 36

2.2 Phnom Penh weather data

It is general to know about the weather condition in Cambodia, as well as in Phnom Penh area which this study case locates in. Briefing information about humidity, wind speed and temperature will be mentioned below.

There is a report describes the typical weather from Phnom Penh International Airport (Phnom Penh, Cambodia) weather station over the course of an average year. It is based on the historical records from 2003 to 2012. The data is shown that the relative humidity typically ranges from 48% (comfortable) to 96% (very humid) over the course of the year, rarely dropping below 36% (comfortable) and reaching as high as 100% (very humid).

Besides, over the course of the year typical wind speeds vary from 0 m/s to 8 m/s (calm to moderate breeze), rarely exceeding 10 m/s. The *highest* average[2] wind speed of 4 m/s (gentle breeze) occurs around August 2, at which time the average daily maximum wind speed is 8 m/s (moderate breeze). The *lowest* average wind speed of 2 m/s (light breeze) occurs around October 14, at which time the average daily maximum wind speed is 5 m/s (gentle breeze).

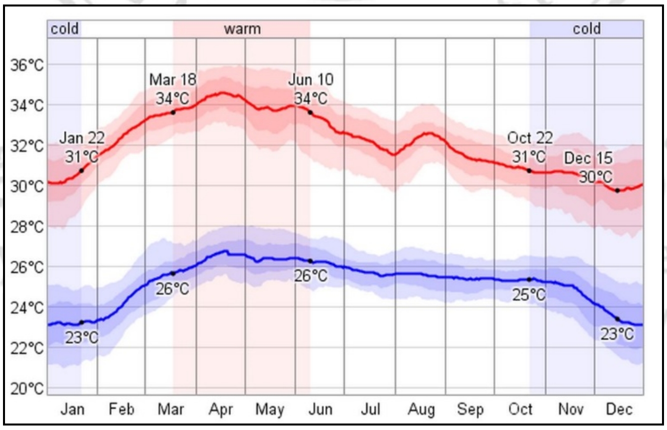

Figure 2.2 Daily high/low temperature for Phnom Penh. The daily average low (blue) and high (red) [8]

[2] In this section, to be clear about wind speed, the source has divided *average* data into two groups which consist of *high average* and *low average*. *High average* was calculated between range of normal average to maximum rate. *Low average* was calculated between ranges of minimum rate to normal average rate.

The temperature is typically varies from 23°C to 35°C and is rarely below 21°C or above 36°C. The warm season lasts from March 18 to June 10 with an average daily high temperature above 34°C. The hottest day of the year is April 18, with an average high of 35°C and low of 27°C. The cold season lasts from October 22 to January 22 with an average daily high temperature below 31°C. The coldest day of the year is January 1, with an average low of 23°C and high of 30°C [8].

The study will mainly pick up temperature weather data references as the input parameter for experiments. Outdoor temperature to be input is 33°C as it is the average high temperature for hot season which should be first consider about improvement of ventilation for row house occupants in order to generate better comfort.

2.3 Comfort factors and standard of comfort zone

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment because there are large variations with both physiologically and psychologically from person to person, it is however difficult to satisfy everyone in a space. The environmental conditions compulsory for comfort are not the same for everyone. However, heat production, metabolic heat production, its transfer to the environment, the resulting physiological adjustments, and body temperatures are principal keys to delimit the acceptance level of thermal environment, the perception of comfort and temperature. There are six primary factors that must be addressed when defining conditions for thermal comfort. The six primary factors are metabolic rate, clothing insulation, air temperature, radiant temperature, air speed, and humidity [9].

In this part, personal factors related to metabolic rate, clothing insulation, and radiant temperature (the relationship between human body heat and environment heat) are neglected. These factors won't be included into experiment boundaries condition, however, these are varies depend on different occupants condition which cannot define sepecically. So, operative temperature, air velocity, and relative humidity are information which take into account to consider in testing.

2.3.1 Operative temperature

Being as rational of this thesis topic which Trombe wall system would use to ventilate row house, standard of comfort zone plays important role by way of parameters to simulate Trombe wall system. Dissatisfaction by warm discomfort for the body as a whole can be expressed by the operative temperature. The satisfactory range of operative temperature (T_o) and humidity for summer are further defined on psychrometric chart in Figure 2.3.

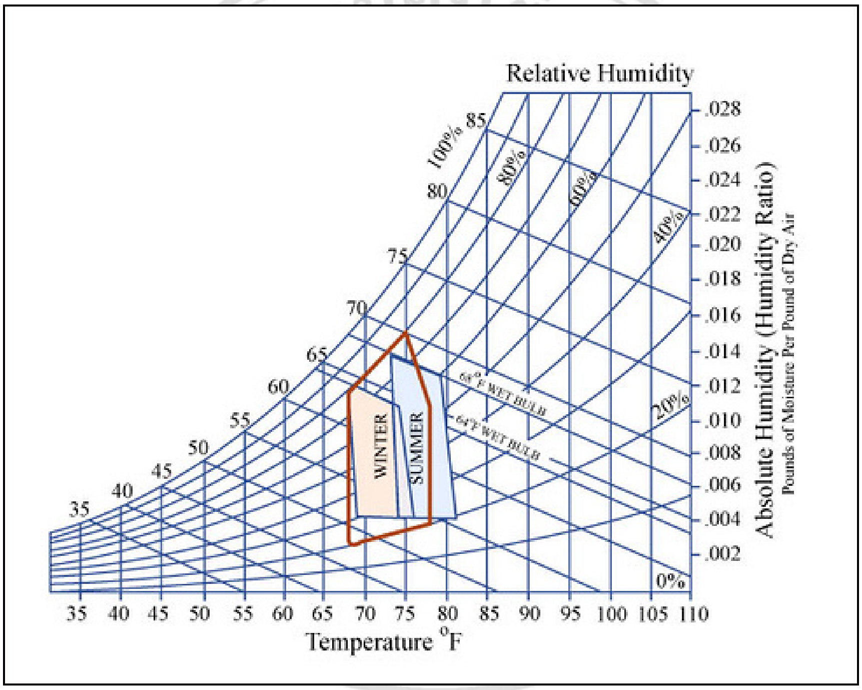

Figure 2.3 ASHRAE summer psychrometric chart for human comfort [10]

According to the chart at summer, temperature of comfort zone are ranged from T_o = 72.5°F to 78.8°F (22.5°C to 26°C) at 20.0°C wet bulb, and T_o= 74.3°F to 80.6°F (23.5°C to 27.0°C) at 2.0°C dew point. However, in Cambodia, there isn't a specific standard mentioned about the satisfactory of indoor wind speed, the surveyed and stretched the new comfort zones for Thai people from Tantasavasdi et al. is a good source to consider in line with the very similar weather in tropic region. These new comfort zones were extended the temperature for comfort on psychrometric chart up to 29.1°C, 29.9°C and 31.3°C for air speed of 0.2, 0.4, and 1.0m/s relatively [11]. Moreover, the bioclimatic comfort chart which is cited by many researchers is also give evident that comfort by ventilation can spread the boundary of comfort zone up 32.2°C (zone B in Figure 2.1).

Due to the chart which describes that from the temperature 27°C, occupants would start feeling discomfort; also, the surveyed data from real case of a pilot case of row house in Phnom Penh viewed that the indoor temperature in house occurs from 27°C, this rate of temperature will be chosen as input parameter for CFD program simulation in term of indoor temperature.

2.3.2 Air velocity

Within thermal comfort temperature range of figure 7, there is no necessary air speed mentioned for thermal comfort. If a mean temperature is increased above the level of comfort zone, air speed is provided to elevate. Base on most assumption, preferable air velocity (increase convective heat loss) is 0.2m/s. Elevated air speed may be used to offset an increase in the air temperature and the mean radiant temperature by not more than 3.0°C (5.4ºF) above the values for the comfort zone without elevated air speed [9].

Besides, the volume of fresh air (make up air) compulsory for proper ventilation is determined by the size and use of the space. Air change rate is a method to measure the quantities of fresh air needed in a unit of time. Fresh air supply to a room can be calculated by multiply air change rate with room volume. It can be defined that the minimum air change rate for general area is at least 4 time, and from 15 times up for kitchen [12]. Moreover, normally in living areas, 0.35 air changes per hour is needed but not less than 15 cfm (7.5 L/s) per person. For kitchen, 100 cfm (50 L/s) intermittent is required or 25 cfm (12 L/s) continuous or with open-able windows [13].

2.3.3 Relative humidity

Relative humidity (or water vapor pressure) influences evaporative heat loss and skin wittedness. Usually, RH between 30% and 70% is comfortable.

Figure 2.1 indicates Bioclimatic comfort chart which was studied by Olgyay, Vector in 1961 and was simplified by Chularlongkorn University Professor, Doctor Sunthorn Boonyathikan, showing the extended range of comfort zone standard. The chart shows the extended range of comfort zone standard. Zone AA and A is too hot and dry for human but it can be improved by supplying water steam to raise up the relative humidity to the range between 50% and 75%. Zone A can also be improved by blowing wind to Zone B in where human body can feel 1°C decreased as the wind speed increases by 2.5Km/h (0.69m/s) or 140FPM. However, zone B is too hot when the speed wind is less than 20 FPM. Zone C has too high level of relative humidity so it needs to decrease the RH level to be comfortable. In zone D, the temperature is acceptable but RH level is too low which needs to be increased to reach comfort zone. Zone E is too cold for human body so to make human body comfort enough, external heat is needed. The main zone using in this study is zone B which has the temperature around 22 to 33°C, and the wind speed about 20 to 700 feet per minute.

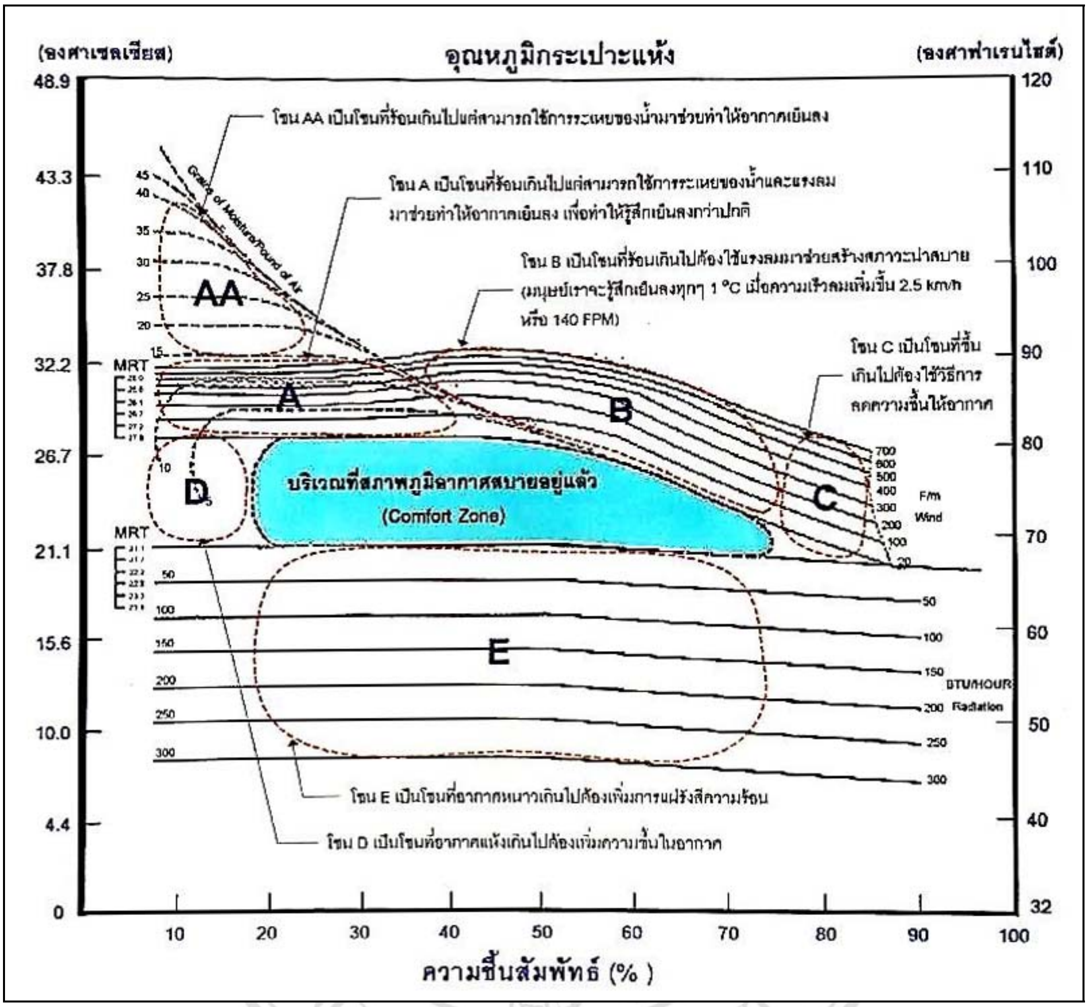

Figure 2.1 Bioclimatic comfort chart by Olgyay, Vector 1961[3] [14]

In this thesis experiment, operative temperature and indoor comfort ventilation rate will be used to confirm with the result of simulation whether the result could achieve standard of comfort or not. So that, this part is necessary to use to compare between the standard with the outcome of Trombe wall system.

2.4 Passive stack effect ventilation strategies for dwelling

2.4.1 Principle of air movement

The architectural design can ensure such natural air movement through two principles [15]. In the first, differences in wind velocity produce a pressure differential

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[3] Olgyay, Victor 1961, "Bioclimatic approach to architectural regionalism", design with climate, 4th printing, New Jersey: Printon University Press, p. 10-13, 19-31, 86-90, 126-177

which results in air flowing from the higher to the lower air pressure region. For indoor air movement caused by a pressure differential, the airflow is steadier in cases that depend more on the suction resulting from low air pressure than on the high air pressure caused by wind force. Obviously, a window or an opening will not create the desired air movement in a room unless an air outlet of some sort is also provided. Experience has shown that air movement is faster and steadier when the area of the openings on the leeward side of a structure is larger than the inlets on the windward side.

In the second, air is warmed, causing convection, with the warm air rising and being replaced by cooler air. A cool draft is created in the space between the warm area and the cool-air intake opening. The rate of airflow caused by convection in buildings is determined by the difference in the level of openings, with greater airflow resulting from a greater difference in the heights of the openings. It is most important when the outside air is still and yet the interior requires ventilation to achieve comfort. Both of these principles have been used in architectural design and town planning in many ways and in several innovations.

2.4.2 Stack effect ventilation strategies

Related to the base case study, there are several kinds of natural ventilation systems which give the possible way to apply for. There are: single-sided ventilation, wind-driven cross ventilation, stack ventilation with sub-slab distribution, wind catcher, and stack ventilation[4].

Single-Sided Ventilation

In single-sided ventilation, driving forces for single-sided ventilation are relatively small and are highly variable. The least attractive natural ventilation solution happens by single sided ventilation. This ventilation provides ventilated air for individual rooms compared to other kind of ventilation. According to the principle of air movement, the effectiveness of this method bases on the height of the window from one

[4] Emmerich, S.J., Dols, and Axley. (2001). “Natural Ventilation Review and Plan for Design and Analysis Tools.” *NISTIR 6781, National Institute of Standards and Technology*, Colorado.

to another. So, this strategy may not work efficiently in row house due to the height of the window from one to another is such short (ground floor front elevation) and simply the fix height of the house wasn’t a good sign to make this work [16].

Wind-Driven Cross Ventilation

Having ventilation openings on opposite sides of a closed space is wind-driven cross ventilation and also called global cross ventilation. In order to have a sufficient ventilation flow, there should be a significant difference in wind pressure between the inlet and outlet openings. Anyway, this method can only work depend on the wind direction. Anyway, according to the layouts of the stydying house, the house seems separated into two part by the stair block. Thus, it is such hard to find a ventilation way for the wind to cross through the house from side to side [16].

Stack Ventilation with Sub-Slab Distribution

By using in-slab or access-floor distribution of fresh air, greater control of air distribution across the building section is observed. However, this method is considered in high cost of construction and cause some effect about the noise [16].

Wind Catcher [5]

Wind catcher is an architectural feature built on the top of a building which looks like a catcher and brings in the fresh air from the surrounding. Wind catcher is a modern version of wind tower which is usually mounted on the roof of the buildings, especially in high-wind region. Using almost the same principle with conventional wind tower, this design can capture the wind at the windward side above the roof level, direct it down into the inner and extract it out at the leeward side, or both catch the wind and extract hot air from the building at the same time within the single element. It can also be considered as a passive stack strategy due to a partial negative pressure created by wind siphon and stack effect.

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[5] International Journal of Academic Research Vol. 4. No. 2. March, 2012, Potential and Constraints of Advance Stack Ventilation Application in the Tropic: A Review, P 151

Though, this strategy relies on wind velocity and direction relative to quadrants, and temperature differential. Therefore, it doesn’t effectively work in low-wind velocity condition and low indoor-outdoor temperature differential, also not suitable for humid climate if evaporative cooling is incorporated [17].

Stack Ventilation

Stack ventilation is where air is driven through the building by vertical pressure differences caused by thermal buoyancy. The warm air inside the building is less dense than cooler air outside, and thus will try to exit from openings high up in the building envelope; cooler denser air will enter openings lower down. The process will keep working if the air entering the building is continuously heated, typically by casual or solar gains.

Stack ventilation is one of the two natural ventilation mechanisms, the other being wind-induced. Since the same openings might contribute to both stack and wind pressure induced flows, they must not be considered in isolation. The effectiveness of the stack effect, i.e. the volume of air that it drives, is dependent upon the height of the stack, the difference between the average temperature of the stack and the outside, and the effective area of the openings [18].

In addition, due to the international journal of academic research about the stack ventilation, advanced stack ventilation for tropic by using wind and solar energy to enhance the performance of natural stack ventilation is recommended. There are solar chimney, double skin façade, and solar roof [19]. However, the research revealed about the disadvantages of those methods such as risk of downdraught during cooler periods (solar chimney), high construction and maintenance cost of glazing systems (double façade), ventilation rate induced is too small and not sufficient (solar roof). So, in this study, another advance technique should be considered is “Trombe wall”. With this technique, suitable to apply to the existing layout of the pilot case. Low cost of construction and renovation to the house, thus expect a better ventilation, are principle keys to try to apply it with experiments.

Trombe Wall

The first concept behind Trombe walls was presented by Edward S. Morse in 1881 [20], thus was name as “Trombe wall” by French engineer Felix Trombe. Later in 1960s, Trombe walls was popular and integrated as architectural elements in buildings by French architect Jacques Michel [21]. Trombe wall technique is one of the passive solar applications adding on stack effect. This wall can be constructed with or without internal vents and on the sun side of a building with a glass external layer and a high heat capacity internal layer separated by an air layer. Heat from the sun passes through the glass and is absorbed by the wall where visible light of solar radiation warm up a high-mass heat storage in channel, but preventing long wave infra-red radiation to radiate back to the outside like the effect of greenhouse. Additionally, heat absorbing wall is normally painted black. After receiving heat, the body or air get lighter and rise up through the outlet hole and vacuum new air through inlet hole. This phenomena occurs continuously.

In conclusion, instead of depending on natural stack effect, advanced stack effect strategies was recommended by prior researchers that it could be more dependable strategy to induce upward air movement and extract it out from the building, especially in low indoor-outdoor temperature differential condition like hot-humid climate region [19, p. 155]. Additionally, the technique of “Trombe wall” will be picked up to study and apply in this case study.

2.4.3 Theories of heat transfer in Trombe wall

Heat transfer is energy in transit, which occurs as a result of a temperature gradient or difference. This temperature difference is thought of as a driving force that causes heat to flow. Heat transfer occurs by three basic mechanisms or modes—conduction, convection, and radiation [22].

The term *conduction* is used to refer to the heat transfer that will occur across the medium. Heat can be conducted through gases, liquids, and solids. The kinetic energy of the molecules of a gas is associated with the property we call *temperature*. In high-temperature region, gas molecules have higher velocities than those in a low-temperature region.

In contrast, the term *convection* refers to heat transfer that will occur between a surface and a moving fluid when they are at different temperatures. The convection heat transfer *mode* is comprised of *two mechanisms.* In addition to energy transfer due to *random molecular motion* (*diffusion*), energy is also transferred by the *bulk*, or *macroscopic, motion* of the fluid. This fluid motion is associated with the fact that, at any instant, large numbers of molecules are moving collectively or as aggregates. Such motion, in the presence of a temperature gradient, contributes to heat transfer.

Besides, the third mode of heat transfer is termed *thermal radiation.* Thermal radiation is energy *emitted* by matter that is at a nonzero temperature. Radiation can emit from solid surfaces, and may also occur from liquids and gases. All surfaces of finite temperature emit energy in the form of electromagnetic waves (or alternatively, photons). While the transfer of energy by conduction or convection requires the presence of a material medium, radiation does not. In fact, radiation transfer occurs most efficiently in a vacuum.

汭The concept of air movement can be appreciated from the study of heat transfer in convection, more specifically, free or natural convection mode. In free convection, fluid motion is due to buoyancy forces within the fluid. Buoyancy in this case occurs due to the combined presence of an air density gradient and a gravitational force that is proportional to density. A mass density gradient arising in a fluid is resulted from the presence of a temperature gradient.

The elevation plays an important role as it effect the amount of thermal energy leading to the difference of density between inlet and outlet. In fact, density is proportional to the temperature, while the magnitude of inlet and outlet velocity depends on the opening area at both points.

The performance of the system can be described in heat transfer. The heat is transferred from the outside to the air in the channel. Absorbing the heat, the properties of the air are changed and result to its movement upwards, as shown in **Figure 2.2**.

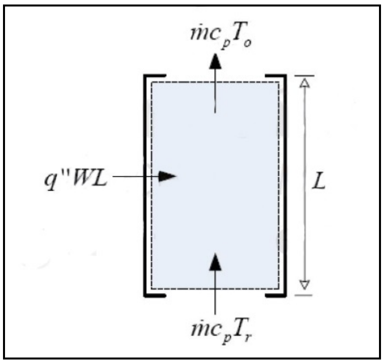

Figure 2.2 The process of heat transfer.

Heat transfer equation is given by

$$q''_{fm}WL = \dot{m}C_p(T_o - T_r) \tag{2.1}$$

where q''_{fm} is heat transfer rate per square meters, W and L are weight and length of the wall in meters, respectively. C_p is heat capacity of the air. T_o and T_r are the temperatures going out and in the system in degree Celsius, respectively. $\dot{m}$ is mass flow rate of the air in channel in kilogram per second, can be calculated from:

$$\dot{m} = C_d\rho_o A_o\sqrt{\frac{gL(T_{fm} - T_r)}{T_r}} \tag{2.2}$$

The equation 2.2 is from Flourentzou (1998), where ρ_o is the density of the air in the channel. A_o is the exchanger area. g is the earth gravity. $C_d = 0.6$ is the heat transfer coefficient at the temperature of T_{fm} calculated from the expansion heat in the channel, as shown in equation 2.3

$$T_{fm} = \gamma T_o + (1 - \gamma)T_r \tag{2.3}$$

According to Hirunlabh (1999), $\gamma = 0.75$ which is the coefficient from the experimental data.

1) Heat transfer in Trombe wall

The performance of Trombe wall in the channel could be calculated in the simplified equation by applying energy balance on three nodes: on the surficial glass, on the surficial wall and in the channel as shown in Figure below.

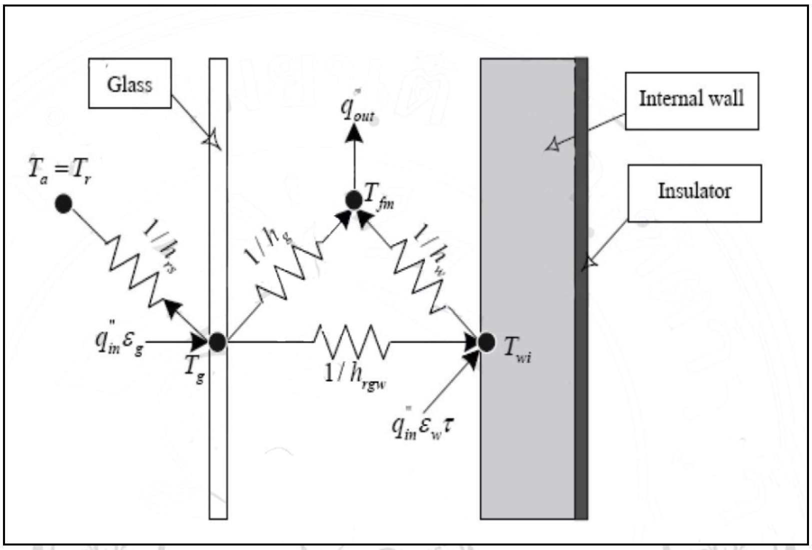

Figure 2.6 Heat transfer in Trombe wall channel [23]

- Energy balance on glass node: equals sum of heat transfer to the air plus radiation of heat transfer to the wall and convection of heat transfer to the air in channel.

$$\alpha_g = h_{rs}(T_g - T_r) + h_{rgw}(T_g - T_{wt}) + h_g(T_g - T_{fm}) \tag{2.4}$$

- Energy balance on channel node: results from the convection of heat transfer from wall and glass added together, thus subtracts heat transfer coefficient from air in channel before heating up.

$$(T_{wt} - T_{fm}) + h_g(T_g - T_{fm}) = \frac{\dot{m}C_p}{\gamma WL}(T_{fm} - T_r) \tag{2.5}$$

- Energy balance in wall node, gets from heat supply which passes through glass to the wall by convection, plus radiation of heat transfer from glass to the wall, then subtracts by the convection of heat on wall which reflex back into the channel.

$$\alpha_w\tau + h_{rgw}(T_g - T_{wt}) = h_w(T_{wt} - T_{fm}) \tag{2.6}$$

Where, h : heat transfer coefficient, $W/m^2 °C$

T_∞ : ambient or air temperature, $°C$

T_s : object surface temperature, $°C$

q''_{in} : heat rate from solar, W/m^2

α_g : glass area, m^2

α_w : wall area, m^2

τ : Thermal coefficient in channel

T_{wi} : Inner wall temperature, $°C$

T_g : Glass temperature, $°C$

T_r : Air surrounding temperature, $°C$

T_{fm} : Flowing air temperature in channel, $°C$

h_{rgw} : radiation heat transfer coefficient from glass to wall, $W/m^2 °C$

h_r : radiation heat transfer coefficient from glass to surrounding, $W/m^2 °C$

h_w : radiation heat transfer coefficient from inner wall to air in channel, $W/m^2 °C$

h_g : radiation heat transfer coefficient from glass to air in channel, $W/m^2 °C$

$\dot{m}$: mass flow rate of air Kg/s

C_p : heat capacity of air

γ : weight factor

W : channel width, *m*

L : channel length, *m*

2) Continuity Equation in Three Dimensions in a Differential Form

The continuity equation expresses the mechanical change analysis of mass in a control volume. The equation is formed by adding up or subtracting mass flow rate at which mass is flowing in and out, and setting the mass flow net is equaled to the change rate of mass ($\frac{dm}{dt}$) within that control volume. Mass flow in and out of the system is equal to the change of mass as given

$$m_{in} - m_{out} = \frac{\partial m}{\partial t} \quad (2.7)$$

Mass flowing in (2.9)

$$m_{in} = (\rho u)_x dydz + (\rho v)_y dxdz + (\rho w)_z dxdy$$

Mass flowing out (2.10)

$$m_{out} = (\rho u)_{x+dx} dydz + (\rho v)_{y+dy} dxdz + (\rho w)_{z+dz} dxdy$$

$$m = \rho dV = \rho dxdydz \quad (2.11)$$

$$\frac{\partial m}{\partial t} = \frac{\partial \rho}{\partial t} dxdydz \quad (2.12)$$

$$\frac{\partial \rho}{\partial t} dxdydz = (\rho u)_x dydz + (\rho v)_y dxdz + (\rho w)_z dxdy - (\rho u)_{x+dx} dydz + (\rho v)_{y+dy} dxdz + (\rho w)_{z+dz} dxdy \quad (2.13)$$

Dividing both sides by $dxdydz$

$$\frac{\partial \rho}{\partial t} = \frac{(\rho u)_x - (\rho u)_{x+dx}}{dx} + \frac{(\rho v)_y - (\rho v)_{y+dy}}{dy} + \frac{(\rho w)_z - (\rho w)_{z+dz}}{dz} \quad (2.14)$$

Since dx dy and dz are too small and following the definition of differential, this becomes

$$\frac{\partial \rho}{\partial t} = -\frac{\partial(\rho u)}{\partial x} - \frac{\partial(\rho v)}{\partial y} - \frac{\partial(\rho w)}{\partial z}$$

 (2.15)

Or rearranging gives

$$\frac{\partial \rho}{\partial t} + \left[\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z}\right] = 0$$

(2.16)

This equation is applicable within control volume for all cases. In some specific case like steady state, the derivative of time is zero, then giving

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (2.17)$$

If the fluid is incompressible or $\rho = constant$, the equation becomes

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \qquad (2.18)$$

So in Trombe wall system, mass continuity will be calculated from one to another set of control volume in channel, from inlet until the outlet, by using equation (2.16.) Then at steady state, equation (2.17) would be applied. However, the mass conservation law doesn’t relate to how the energy converts or transfers.

3) Momentum Equation

Newton’s second law stated that the sum of the forces on the particle is equal to the rate of change of momentum of a fluid particle:

$$\Sigma\vec{F}=\frac{D}{Dt}(m\vec{V}) \qquad (2.19)$$

Figure 2.6 shows a fluid element’s state of stress in terms of the pressure and nine viscous stress components.

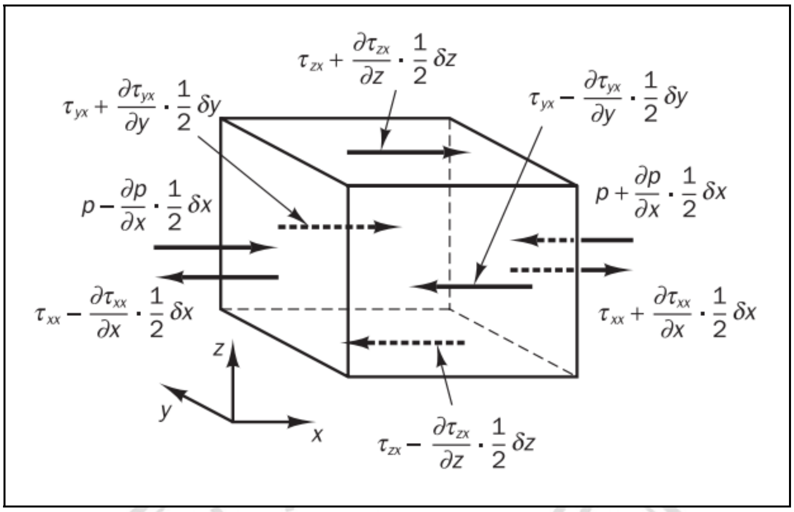

Figure 2.6 fluid element's state of stress in terms of the pressure and nine viscous stress components [24]

On the both sides perpendicular to the x direction, we have

$$\left[\left(p - \frac{\partial p}{\partial x}\frac{dx}{2}\right) - \left(\tau_{xx} - \frac{\partial \tau_{xx}}{\partial x}\frac{dx}{2}\right)\right] dydz + \left[-\left(p + \frac{\partial p}{\partial x}\frac{dx}{2}\right) + \left(\tau_{xx} - \frac{\partial \tau_{xx}}{\partial x}\frac{dx}{2}\right)\right] dydz = \left(-\frac{\partial p}{\partial x} + -\frac{\partial \tau_{xx}}{\partial x}\right) dxdydz \tag{2.18}$$

The net force in the x-direction on the pair of faces (N, S) is given by

$$-\left(\tau_{yx} - \frac{\partial \tau_{yx}}{\partial y}\frac{dy}{2}\right) dxdz + \left(\tau_{yx} - \frac{\partial \tau_{yx}}{\partial y}\frac{dy}{2}\right) dxdz = \frac{\partial \tau_{yx}}{\partial y} dxdydz \tag{2.19}$$

Finally that on faces T and B is

$$-\left(\tau_{zx} - \frac{\partial \tau_{zx}}{\partial z}\frac{dz}{2}\right) dxdy + \left(\tau_{zx} - \frac{\partial \tau_{zx}}{\partial z}\frac{dz}{2}\right) dxdy = \frac{\partial \tau_{zx}}{\partial z} dxdydz \tag{2.20}$$

The x-component of the momentum equation is

$$\rho \frac{Du}{Dt} = \frac{(-p + \tau_{xx})}{\partial x} + \frac{\partial \tau_{yx}}{\partial y} + \frac{\partial \tau_{zx}}{\partial z} + S_{Mx} \tag{2.21}$$

Similarly, the y-component of the momentum equation is

$$\rho \frac{Dv}{Dt} = \frac{\partial \tau_{xy}}{\partial x} + \frac{\partial(-p + \tau_{yy})}{\partial y} + \frac{\partial \tau_{zy}}{\partial z} + S_{My} \tag{2.22}$$

The same as the z-component of the momentum equation is

$$\rho \frac{Dw}{Dt} = \frac{\partial \tau_{xz}}{\partial x} + \frac{\partial \tau_{yz}}{\partial y} + \frac{\partial(-p + \tau_{zz})}{\partial z} \tag{2.23}$$

4) Energy equation

The energy conservation equation is derived from the first law of thermodynamic, which stated that the rate of change of energy of a fluid particle equals the rate of heat adding to the fluid particle plus the rate of work done on the particle:

The rate of increase of energy per unit volume is given

$$\rho \frac{DE}{Dt} \tag{2.24}$$

The increasing rate of net liquid particles are composed of the work of the weight of the Body forces and the rate of work done on the surface. The surface forces is the product of speed and force in the same direction. The overall rate of total work done on the fluid can be written as follows.

$$f.\vec{V}(dxdydz) - \left[\left(\frac{\partial(up)}{\partial x} + \frac{\partial(vp)}{\partial y} + \frac{\partial(wp)}{\partial z}\right) + \frac{\partial(u\tau_{xx})}{\partial x} + \frac{\partial(u\tau_{yx})}{\partial y} + \frac{\partial(u\tau_{zx})}{\partial z} + \frac{\partial(v\tau_{xy})}{\partial x} + \frac{\partial(u\tau_{yy})}{\partial y} + \frac{\partial(u\tau_{zy})}{\partial z} + \frac{\partial(w\tau_{xz})}{\partial x} + \frac{\partial(w\tau_{yz})}{\partial y} + \frac{\partial(w\tau_{zz})}{\partial z}\right] dxdydz \tag{2.25}$$

When $f.\vec{V}(dxdydz)$ is the force exerted by the weight of the body (Body forces.)

The amount of heat generated is equal to or removed from the fluid.

$$\rho\dot{q}(dxdydz) \tag{2.26}$$

The net amount of heat transferred through the fluid is.

$$-\left(\frac{\partial \dot{q}_x}{\partial x}+\frac{\partial \dot{q}_y}{\partial y}+\frac{\partial \dot{q}_z}{\partial z}\right)dxdydz \tag{2.27}$$

The net heat flux to the fluid flow is.

$$[\rho\dot{q}-\left(\frac{\partial \dot{q}_x}{\partial x}+\frac{\partial \dot{q}_y}{\partial y}+\frac{\partial \dot{q}_z}{\partial z}\right)]\,dxdydz \tag{2.28}$$

Or

$$[\rho\dot{q}+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)]\,dxdydz \tag{2.29}$$

Since the second fluid movement and thus changing the energy of the fluid, it also changes the internal energy and kinetic energy.

$$\rho\frac{D}{Dt}(e+\frac{V^2}{2})dxdydz \tag{2.30}$$

Energy equation can be written in the form of differential equations as follows.

$$\rho\frac{D}{Dt}\left(e+\frac{V^2}{2}\right)=\rho\dot{q}+\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)-\left(\frac{\partial(up)}{\partial x}+\frac{\partial(vp)}{\partial y}+\frac{\partial(wp)}{\partial z}\right)+$$
$$\frac{\partial(u\tau_{xx})}{\partial x}+\frac{\partial(u\tau_{yx})}{\partial y}+\frac{\partial(u\tau_{zx})}{\partial z}+\frac{\partial(v\tau_{xy})}{\partial x}+\frac{\partial(v\tau_{yy})}{\partial y}+\frac{\partial(v\tau_{zy})}{\partial z}+\frac{\partial(w\tau_{xz})}{\partial x}+\frac{\partial(w\tau_{yz})}{\partial y}+\frac{\partial(w\tau_{zz})}{\partial z}+$$
$$\vec{f}.\vec{V} \tag{2.31}$$

For a compressible fluid (Compressible Fluid) energy equation is often expressed in terms of enthalpy (h) below.

Specific enthalpy is

$$h = e + \frac{P}{\rho} \tag{2.32}$$

Total enthalpy can be calculated from:

$$h_o = h + \frac{V^2}{2} \tag{2.33}$$

An incompressible fluid can be represented in the energy conservation equation below

$$e = c_v T \tag{2.34}$$

Where *e* is internal energy; C_v is Specific heat; *T* is Temperature

The energy equation is used as the correlation of internal, kinetic and gravitational potential energy. This equation usually needs the assist of the mass conservation, momentum equation to solve the problems.

2.5 Previous studies

2.5.1 Types and materials of Trombe wall

There are several types of Trombe wall in application from the past till now. Omidreza Sadatian et al. [25] investigated about the opportunities and challenges in research and development of Trombe wall. The configuration of Trombe wall are categorized into 9 types such as: (1) classic trombe wall, (2) Zigzag trombe wall, (3) Water Trombe wall, (4) Solar transwall, (5) Solar hybrid wall, (6) Trombe wall with phase-change material, (7) Composite Trombe wall, (8) Fluidized Trome wall, and (9) Photovoltaic (PV) Trombe wall. This paper also analyzed about the efficiency of vent, size, materials, disadvantages, advantages, and economic effect of the system. The optimal ratio of Trombe wall area compared to other side of wall should be 37%. Dark color are recommended as it absorb energy much better and insulation can also enhance Trombe wall performance by up to 56% with the advantage to lighter mass wall. Beside disadvantages of uncertainty heat transfer, insufficient of beauty and aesthetic, Trombe wall is a good renewable energy system which give sustainable economic benefits.

Some researchers were trying to apply many kind of materials and multiple combination techniques in order to search for the best performance of Trombe wall. J. Hirunlabh et al. [26] took a test on metallic solar wall separated with a gap from glazing panel to remove heat from dwelling. Air mass flow rate received from the scheme was about 1.01-0.02 Kg/s with surface area $2m^2$ and 14.5cm air gap. This proposed system verified both the reduction of heat gain in house and economical saving on installing cost.

Tengfei (Tim) Zhang et al. [34] researched about the prediction of airflow rate through a ventilated wall module. This investigation calculates the volumetric flow rates versus the driving pressure by developed a lumped correlation analysis model, afterward implements by computational fluid dynamics (CFD) to predict the ventilated wall performance. A high-precision Micro-manomester was brought as the tool to measure both pressures and induced volumetric flow reates. It is found that experimental data obtained a good consent result with correlation analysis. Nonetheless, CFD calculation achieved quite similar result with the correlation, especially from the heat flux $500W/m^2$ up.

Jaran R. and Pithan P. [27] the other proposed glass solar chimney (GSCW) wall compared to single layer glass wall to apply in tropic region. The result found that glass solar chimney had created a lower indoor temperature than one layer glass wall as an average difference in temperature of 2.46-1.80 °C,1.63-1.30 °C and 1.36-1.28 °C for winter, rainy, and summer respectively. GSCW was good concept to apply on mini buildings which stand-alone outdoor.

Moreover, some studied about the combination of roof solar collector and vertical chimney [28]. By carried out experiment in actual environment in Malaysia. From the experiments, temperature difference between ambient and in channel was from $6.2^{o}C$ to $9.9\ ^{o}C$ by radiation $552W/m^2$ to $877W.m^2$. Air velocity at outlet of each prototype was highest in around 0.54m/s.

2.5.2 Advantages of Trombe wall

Trombe wall is a friendly passive design strategy to reduce building energy using load by both circulate air from indoor to outdoor and store heat in building. Trombe walls scheme has been applied in several case studies not only to prompt ventilation but also to heat building in order to lessen operating energy consumption in cold weather. Such as an experiment case of “Mozart” house in Lyon, France, two Trombe walls installed at south side of the house help to save energy for heating around 20% for a year [29].

Eduardo Krüger et al. [30] led test cells to evaluate about Trombe wall system in sub-tropic region. The system yielded high potential in reducing energy consumption for cooling and heating the indoor space of about 30% a year. Especially for sub-tropic region analyzed, high solar elevation in summer urge the system performed sensibly well than in winter. The result encouraged the other experiments to insulate the back side of absorbing-heat-wall to enhance the performance of the system which can increase up to 56%. Furthermore, the dampers was introduced to use automated opening and shutting to help prevent the reverse unwanted flow of the air vent.

Solar chimney is a similar kind of Trombe wall technique which uses heat to induce indoor ventilation. As long as vertical solar chimney was found as another suitable method for tropical condition, Agung M. Nugroho [31] conducted a research to find out the effect of solar chimney geometry for stack induced ventilation strategies. A solar chimey geometry size 1m width, 3m length, and 3.5m height was installed on a single story row-house located in Malaysia as study case. Thus CFD (FloVent) was used as operating tool to investigate airflow as well as solar radiation. As the result, the system can induce wind velocity up to 0.6m/s. The study gave the assumption that the use of Solar chimney provide a better indoor ventilation than a non-chimney terrace house.

2.5.3 The Study of Trombe wall ratio

Researchers were also consider about parameters which effect the performance of Trombe wall, thus seeking for best ratio of channel gap to gain more capacity of the system. Guohui Gan [32] conducted the research about parametric study of Trombe walls for summer cooling buildings, found out that CFD program was validated compared to real experiments. The study also investigated on the effect of the gap between wall and glazing, wall height, glazing type, and wall insulation. The prediction of ventilation rate increased while the temperature and heat rate increased. While the inlet and outlet width was fixed in smaller size than the channel gap, the air flow rate was mostly unaffected by variety of channel width. It is recommended that inlet and outlet height should be equally increased by the increasing of channel gap width. Anyway, the interior surface of Trombe wall should be insulated to maintain heat transfer from the wall into the room.

S.A.M. Burek et al [33] reported on an experimental study about air flow and thermal efficiency characteristics in solar chimneys and Trombe walls. With the area of 1m² and the channel depth between 20 to 110mm of solar chimney, the input heat ranged from 200 to 1000W is inserted. Since temperature and air velocity are recorded throughout the test, the results give out the correlation parameters of mass flow and thermal efficiency in dimensionless form. First, the mass flow rate through the channel was a function of heat input and channel depth. Second, the thermal efficiency of the system was a function of heat input, and not depend on the channel depth.

Also, Aniroot Tesing [35] studied about the relationship between heat flux and mass flow rate in gypsum board trombe wall. Testing referred to find out best performance of the system varies between the gap and wall height ratio. For the area of wall 0.5m×1m model, the outcome showed that the maximum air flow rate reached the value of 14.2×10^{-3} Kg/s by D/L ratio 0.25 with heat flux 1000W/m². However, the highest thermal efficiency gave its best at ratio 0.05, the mass flow rate resulted lesser.

Akkeepas Leerasetthakorn [36] studied the performance of the glazing trombe wall effected by the proportion between width and height of the air gap (D/L), and mass flow rate. The experiments were carried out in a real model cube house with 3-meter-edge length, with 0.15m equally height of inlet and outlet, heated by solar energy in winter and summer. The greater the D/L, the faster the ventilation goes until the optimum level. The D/L ratio value providing the best efficiency in winter was around

0.053 in the range of heat flux around 700-800W/m^2, while that in summer would be 0.07 in the range of heat flux around 180-200W/m^2. Comparing to common wall, it also found that the glazing trombe wall could save up 1-38% of the electricity on air-conditioner.

Phanuphong Thongnut [23] explored the most effective design of the Trombe wall, considering the heat flux applied, mass flow rate of air in a channel and wall aspect ratio (channel gap and wall height). The testing model of Trombe wall was made of concrete for internal wall and a glass pane covering on the external. The internal wall was insulated on inner surface and used halogen lamp as the replacement source of sun radiation. The heat flow rate was changed from 200 to 1000 W/m^2. The results showed that in the steady state, the air flow rate in the channel was constant in all cases of heat inputs. It also found that the air mass flow rate increased with the increase of the heat flux input and the decrease of air gap depth and the air flow rate reached a maximum at the aspect ratio of 0.05 (channel gap and wall height) and the heat flux input of 1000 W/m^2.

The simulation would be run by computational fluid dynamic (CFD), since this program was validated compared to real experiments as well as its revealing results in feasible visualization, and low cost of labor and equipment [32] [37].

About sun radiation, the total amount of energy from the sun is measured on a unit area of surface perpendicular to the direction of propagation of the radiation at mean earth-sun distance outside the atmosphere per unit time. According to the World Radiation Center (WRC), total amount of energy value is 1367 W/m^2 and is changed depends on the distance to the sun on the certain time of year. It is approximately 3.3% higher and lower in January and July, respectively. However, the value of this energy after going through the atmosphere hitting the ground is around 1120 W/m^2 [38]. Therefore, the value selected for this simulation were 200, 400, 600, 800 and 1000W/m^2 due to the assumption of heat flux from the sun from low light till the highest light during a day.

According to these studies, it is found that Trombe wall technique is a good strategy which is suitable to apply with the aim of ventilation creation. In addition, previous researches were also agree that CFD program is a reliable program to use as a measuring tool for air flow process. Nevertheless, previous research gave detail information about the most effective ratio for Trombe wall scheme which are very important information for this thesis parameters setup. Due to Phanuphong T. [23] the temperature gotten at both wall and glass, are main data for boundaries condition of the experiments. Therefore, the best ratio between channel gap and wall height to apply into this thesis is 0.05. Thus, temperature results on both wall and glass will be deliberately indicated in chapter of methodology.

2.6 XFlow Computational Fluid Dynamics

Computational fluid dynamics (CFD) technique is an art of replacing the governing partial differential equations of fluid flow with numbers. It has become popular due to the fact that supports and complements both of pure experiment and theory as well as its illuminating results, and low cost of labor and equipment. Particularly in the last two decades, the CFD technique is broadly used to predict the air movement within rooms and around buildings. The CFD is also widely used to determine thermal comfort value. Numerical results showed a good agreement with experimental data. Like the CFD, flow visualization has greatly assisted fundamental understanding of a wide variety of fluid dynamic phenomena [37].

Hence, to measure the effectiveness of the stack effect which will be apply, a reliable CFD program, XFlow [39], would be chosen to simulate. Deliberating as the trusted simulation program, XFlow program is the one which is recommended from the experts and has been applied in many potential projects which designed for engineering analysis. It uses a proprietary, particle-based, fully Lagrangian approach which can easily handle traditionally complex problems such as aerodynamics, aero-acoustics, moving parts, free surface flows and fluid-structure interaction. Key features and technologies of XFlow:

Meshless approach to CFD: The meshless approach within XFlow is particle-based and fully Lagrangian, which means that classic fluid domain meshing is not required. Also surface complexity is not a limiting factor. XFlow can handle moving bodies and deformable parts, and is tolerant to the quality of the input geometry.

Particle-based kinetic solver: XFlow features a novel particle-based kinetic algorithm that resolves the Boltzmann and the compressible Navier-Stokes equations. The solver features state-of-the-art Large Eddy Simulation (LES) modelling, and advanced non-equilibrium wall models.

Single consistent wall model: XFlow uses a unified non-equilibrium wall function in order to model the boundary layer. This wall model works in all cases, meaning it is not necessary to select between different algorithms and deal with the different limitations of each scheme.

Adaptive wake refinement: The XFlow engine automatically adapts the resolved scales to the user's requirements, refining the quality of the solution near the walls and dynamically adapting to the wake while the flow develops.

Advanced modelling capabilities: XFlow is capable of handling large and complex models, and greatly simplifies the setup of analysis with moving parts, hierarchical structures, enforced or rigid body motion, and contact modelling.

Advanced analysis capabilities: The XFlow solver also features thermal analysis, conjugated heat transfer, transonic and supersonic flows, flow through porous media, non-Newtonian flows, and complex boundary conditions including the porous jump and fan models.

Near-linear scalable performance: XFlow is fast and efficient, even on a standard desktop PC. It is fully parallelized for multi-core technology with near-linear scalability.

Easy-to-use interface: XFlow provides a unique and novel interface and working environment for the user, including pre-processor, solver and post-processor fully integrated in the same environment, state-of-the-art visualization, and configurable layout.

In summary, to be specific on this thesis, necessary boundaries conditions which program needs are:

- 3D model of study case which wall, glass, inlet, and outlet surface were already defined.
- Initial temperature field
- Gravity
- Air density
- Operating temperature
- Temperature on glass, wall
- Pressure at inlet