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NUMERICAL SIMULATION AND EXPERIMENTAL STUDIES ON RESIDENTIAL HOME USING EVAPORATIVE COOLING AND VERTICAL VENTILATION

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ABSTRACT

The limitation of land in urban area leads to the existence of land slowly omitted and changed to be functioned room. The additional room itself will be reducing thermal comfort in the house. To maintain thermal comfort, some alternative solutions are directed in conjunction with modern technologies, for instance using air conditioning system. However, the solution proved that it can produce more energy extravagance, and stimulate global warming (Givoni, 1998). Therefore, alternative natural cooling system with less energy consumption for getting comfortable level in residential house and similar building is required. The work described here is a computational fluids dynamics (CFD)study aimed at validating the numerical method with experimental data available from a house incorporated with vertical ventilation system which existed at Surakarta Indonesia (Azizah R. and Qomarun, 2014). A detailed computational model of the house device has been established. Initial CFD work has focused on establishing the relationship between ambient wind speed and relative humidity and temperature, and later comparing the results with the existing *experimental data. Main outcomes are conformable level and promising of using natural cooling system. Detailed flow field are visualized that were not seen from the experiments. Further simulation work to model the house performance with water spray evaporation is addressed in brief and the results are plotted into comfortable zone using psycrometric chart.*

Keywords: Comfort zone, evaporative cooling, CFD

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1. INTRODUCTION

The residential house commonly has an additional land both in the front and behind to fulfill the requirements of occupant's thermal comfort. The existence of extra land also gives space for air change rate, so that the perfect air circulation in housing can be improved. However, due to limitation of land in urban area, the existence of land slowly is missing out and changed to be functioned room. The additional room itself will be reducing thermal comfortable level in the house.

The natural thermal comfort can be gained by the one of alternative systems so called evaporative cooling, by producing evaporation effect in the room. Cooling with evaporation technique can work effectively while combining with better air circulation. Ventilation systems or louvers in the house are one of feasible ways to gain fresh air and also for escaping humid air from the interior, resulting in better air circulation accordingly. The evaporation effect is basically changed of substance phase using latent heat calorie in place, where latent heat is the energy absorbed by or released from a substance during a phase change from a gas to a liquid or a solid and vice versa. The evaporation process gave temperature and relative humidity in the space effectively. The evaporative cooling and vertical ventilation design used in the natural cooling can influence the thermal comfort produced. Therefore, further researches are required to study alternative natural and passive cooling.

The experimental study to investigate thermal comfort characteristics resulted by a ventilation design and evaporation method would be very costly. Beside of designing process, it also needs the procurement of measurement apparatus as many as positions that will be measured in getting air characteristic uniformly positions. Since, air properties may be changed from time to time depending on local weather conditions.

Research development using software and computational based method is promising and it can help researchers in simulating of actual phenomenon process. One of methods used is so-called Computational Fluid Dynamic (CFD). ANSYS is one commercial software used for completing CFD analyses in this study. The software can deal with multi-physics problems, including mechanical, heat transfer and fluid as well as the case related with acoustics and electromagnetics, etc. In this work, the case study will be analyzed and simulated using Ansys CFX-15, focusing on evaporative cooling effect in residential home incorporated with vertical ventilation. Numerical data collected then are compared with the experimental data studied simultaneously.

2. LITERATURE AND THEORETICAL REVIEW

2.1. Literature Review

(Azizah R. and Qomarun, 2014) investigated alternative vertical ventilation in supporting thermal comfort of residential home at urban area. Their research was conducted experimentally. In design, step of building was conducting with separated floors on base and completed with porous in wet area. Whereas, vertical ventilation was designed by omitting back walls, giving a gap of 30 cm from the wall of the neighboring house. Thermal investigation was done by measuring temperature, relative humidity (RH) and air velocity at 28 measurement points, along the avenue in the front, at interior and exterior of the house, respectively. The results of thermal investigation showed that vertical ventilation and water evaporation on the floor was able to reduce temperature by 2^{o}C compared with ambient temperature and also in case of air change rate encountered by 0.1 m/s on average. (Masak et al., 2000) described and simulated using a CFD model for a passive evaporative cooling in a hypothetical building designed by Ford & Associates at central of Seville Spanyol using CFX-4.2. CFD simulation was done to investigate air flow, temperature and RH resulted in the building with passive evaporative cooling system that operated at no wind condition and with air flow velocity of 4 m/s from south and north direction, with temperature of 35^{o}C and RH of 34% used in Sevilla. Simulation results at no wind condition obtained with ambient temperature of 29^{o}C for lower room and for higher room it tends to have increased temperature. The simulation with air velocity, downward flow at atrium room showed to be unbalanced due to air velocity above the inlet, then temperature and RH were also to be unbalanced. (Sarjito and Riyadi T.W.B., 2013, 2014) numerically studied the evaporative cooling effect with multi-stage downdraught evaporative cooling. CFD simulation was carried out to reveal the evaluation of cooling performance of multi-stage by incorporating water spray and applying the best wind catcher investigated previously. Simulation was conducted by integrating evaporative cooling apparatus in a hypothetical building of two floors by deemed hot and dry weather. In that research, operation by varying wind speed to investigate of cooling effect was also carried out. Typically, simulation result showed that the more air velocity given the more temperature reduced, and the RH increased on the floor accordingly. Literature review below is not only on theoretical but also of some empirical studies.

2.2. Theoretical Review

2.2.1. Air conditioning system

The air conditioning system is a cooling process or heating air so that temperature and relative humidity suitable with requirement for comfortable of occupants living in space. (Frick, 2007) defined thermal comfortable considering three important aspects, namely air temperature, RH and air change rate. Thermal comfort for static air can be divided into three categories: (1) nice cool, with effective temperature of 20.5^{o}C-22.8^{o}C (2) optimal nice with effective temperature of 22.8^{o}C-25.8^{o}C and (3) nice warm with effective temperature of 25.8^{o}C-27.1^{o}C. Thus, nice area for human physically in static air could be achieved at the room condition with temperature of 21^{o}C-27^{o}C and RH of 20%-70%, respectively. Furthermore, thermal comfortable for moving air flow in maximum speed of 0.1m/s, comfort area is achieved in the range of temperature 25^{o}C-35^{o}C and RH of 5%-85%.

2.2.2. Evaporative cooling

The evaporative cooling is occurred due to water evaporation on free surface with the auxiliary air flow (Stoeker, 1982). Evaporative cooling also happens when steam of water added to the air having RH less than 100%. The application of evaporative cooling can be divided into five categories (Bowman, 2000) as:

1. Indirect passive evaporative cooling

   The indirect passive evaporative cooling includes a conduction heat transfer prices from solids to liquids, where cooling process coming from evaporation source of water to the air. For instant, pond, spray water, moving water at the roof of residential house.

2. Indirect active evaporative cooling

   In this process, ambient air is flowing through a cooling stack, and evaporative cooling is occurred due to the contact of ambient air and wetted heat transfer apparatus. Heat transfer is occurred in convective mean, and there is no increase in RH at cooled rooms.

2.2.3. Direct evaporative cooling

The direct evaporative cooling includes water evaporation dropped at air flow. For examples, transpiration process of tree that is placed in humid area, fountain, spray and pond and cooling chimney.

2.2.4. Direct active evaporative cooling

This is principally the same as indirect active evaporative cooling, and the only differences are it is cooling the air (because its contact with wet pad) then forwarded to space is being cooled.

2.2.5. Two steps evaporative cooling

The two-step evaporative cooling is a combination between the direct active evaporative cooling with the indirect evaporative cooling, and it is commonly used in lower dry wet bulb temperature.

2.2.6. Psychrometric chart

Psychrometric is the study of properties air and steam of water mixing, and having important meaning in air conditioning technique, as atmospheric air not totally dry. Evaporative cooling process can be seen in figure.1 (i.e. phase 0 to 1), it includes cooling with latent heat from air due to water evaporation.

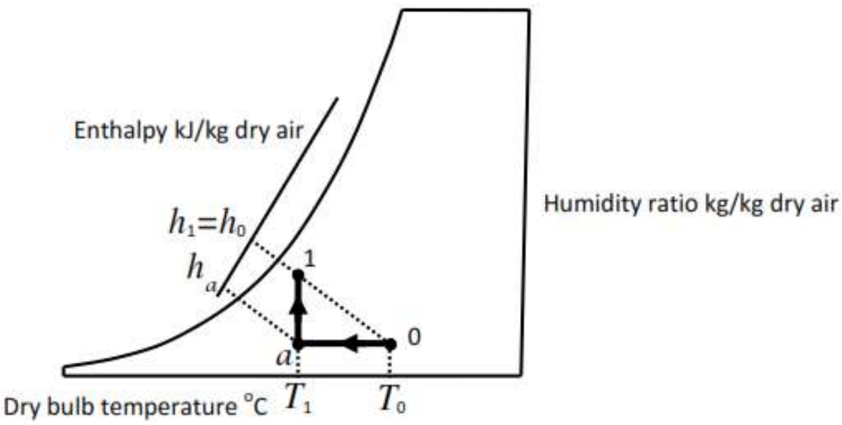

Figure 1. Evaporative cooling process.

The ideal evaporative cooling is an adiabatic process, where enthalpy at the final process is the same as enthalpy at initial process ($h_0=h_1$). There is no benefit or drawback in the system, total latent heat of cooling is balanced with total thermal energy absorbed by water evaporation. If thermal energy added into the system then enthalpy at the end state will be increased.

2.2.7. Relative humidity (RH)

The relative humidity is a ratio between partial pressure of water steam in mixing to pressure of saturated water vapor in certain temperature. Relative humidity is expressed using the following equation:

$$\varphi = \frac{P(H_2O)}{P^{'}(H_2O)} \times 100\% \ldots\ldots\ldots\ldots(1)$$

where:

φ = Relative Humidity (%)

P (H_2O) = Partial pressure of water steam in mixing

P' (H_2O) = Saturated pressure of water at certain temperature

2.2.8. Dry bulb temperature (DBT)

The dry bulb temperature is room air temperature found from measurement using link Psychrometer on dry bulb temperature. The dry bulb temperature is plotted in vertical line started from horizontal axis in lower position of Psychrometric chart. The changing in dry bulb temperature indicates of changing in sensible heat.

2.2.9. Wind Shear Effect(WSE)

The wind speed just at ground level having lower speed compared with higher air layer. Surface effect is often knew with wind shear effect which is condition of boundary layer in no-slip adiabatic applied at entire surface and incoming air velocity changed with shear effect of air with cross sectional area $V_{(y)}$that determined use the following expression (Smith et al. 2002)

$$\frac{V_{(y)}}{V_{ref}} = \left(\frac{y}{H_{ref}} \right)^{\alpha} \ldots\ldots\ldots(2)$$

In this equation, $V_{(y)}$is representing of incoming air velocity (m/s) at height of y(m), V_{ref}, is reference air velocity at height reference height of H_{ref}, and power of α is value of surface roughness on the appropriate area.

3. METHODOLOGY

3.1. Experimental Setup

Experiment setup was done in a previous study of (Azizah R. and Qomarun, 2014) throughout three steps as: (1) designing step; (2) construction step; and (3) testing step. The model house is illustrated in figure 2.

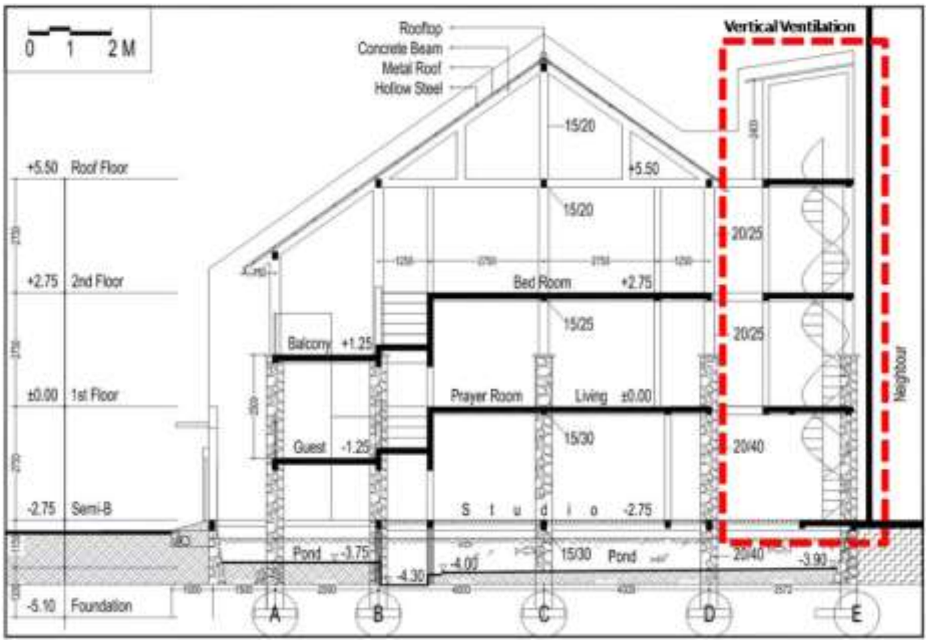

Figure 2. Cross sectional area and vertical ventilation position.

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Once steps one and two are completed over one year period then testing step in phase three was carried out in year 2014. The testing step was done from early morning till night in 6 time intervals of (1) at 06.00-07.00 am; (2) at 09.00-10.00 am; (3) at 12.00-13.00 pm; (4) at 15.00-16.00 pm; (5) at 19.00-20.00 pm; and (6) at 22.00-23.00 pm, respectively. Thermal investigation was conducted by measuring air velocity, RH and temperature at 28 measurement points (MPs). The MP locations were distributed in three different locations of (1) at avenue in the front of the house; (2) at the exterior; and (3) at the interior of the house. Temperature measurement was carried out using digital thermometer of Digital Humidity and Thermometer (Model LM-81HT), and it was measuring RH and temperature. Meanwhile, f Digital Anemometer (Model LM-81AM) was used or measuring air velocity.

The house is located at Karangasem Laweyan, Solo, Indonesia with land area of 117m^2, building area of 170 m^2 and number of floor of 4 layers. The experiment measurement of 28 MPs was conducted manually and alternately from one to another locations, therefore this was possible of minor reading errors introduced in difference situations so that fluid property were different and changed time to time.

3.2. Simulation Setup

Simulation setup was initiated by designing model as same as the experimental apparatus using computer aided design (CAD) so called SolidWork software. The model produced then to be simulated using ANSYS CFX 15. Modelling was initiated by gathering relevance information to the context throughout literature study and geometry was suited with house environment as used by (Azizah R. and Qomarun, 2014). Further step was produced three dimensional house using SolidWork 2014 by reference to experiment apparatus design as shown in Figure3 as follows;

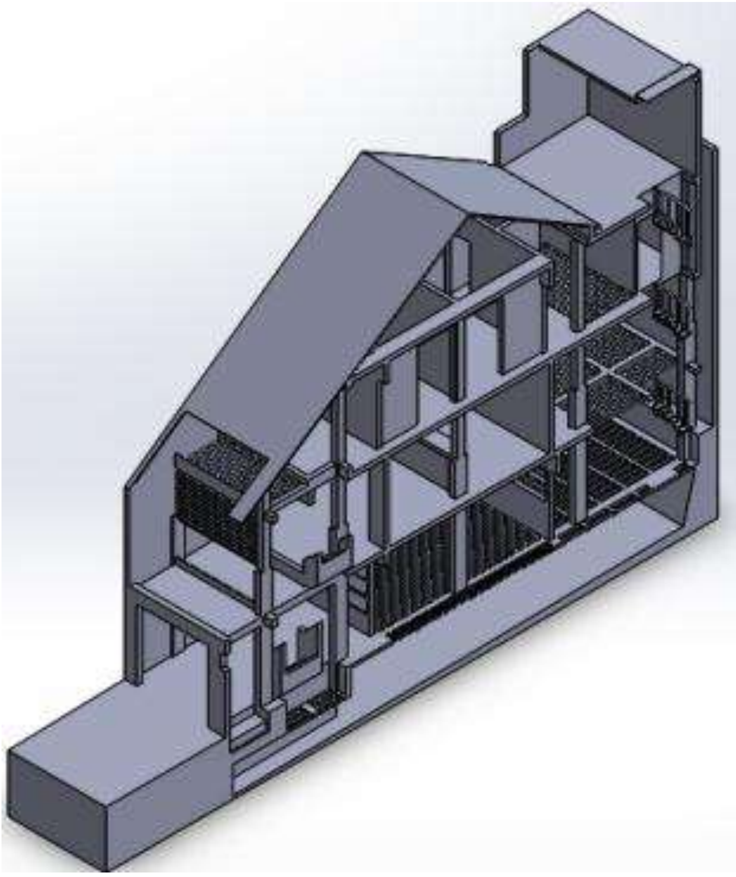

Figure 3. Design of residential house in isometric view.

Figure3 illustrates the CAD model that has been produced then was imported into ANSYS Workbench and completed with computational domain. Meshing process was performed with unstructured mesh producing 27,323,020 elements and 5,026,715 nodes as seen in Figure 4. The boundary conditions were presented in Table 1.

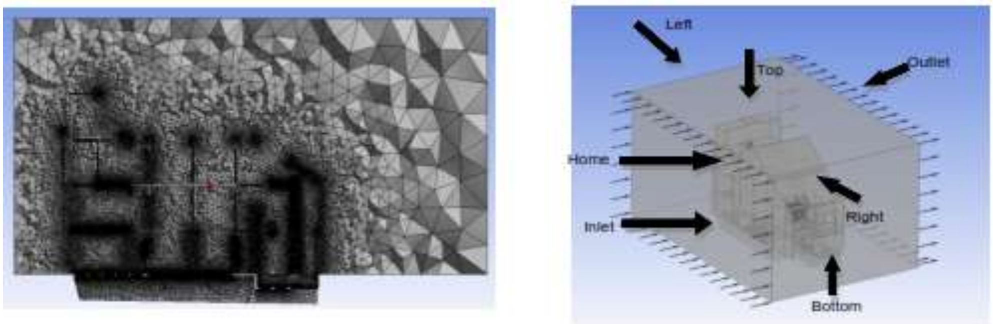

Figure 4. Contour of mesh.

Table 1. Setting boundary condition

Domain	Boundary Type	Location	Mass and Momentum	Heat Transfer	Mass Fraction
Home	Wall	BodySurface	Free Slip	-	-
Bottom	Wall	Bottom	Free Slip	-	-
Inlet	Inlet	Inlet	Velpro	(28-33)°C	0.016-0.021
Outlet	Outlet	Outlet	Free Slip	-	-
Left	Wall	Left	Free Slip	-	-
Right	Wall	Right	' Free Slip	-	-
Top	Wall	Top	Free Slip	-	-

After running process, results will be compared with experimental data of Ronim, (Azizah R. and Qomarun, 2014) to analysis characteristics differences from both of experimental and simulation results. The measurement points each position and floor are illustrated in Figure 5 as follows;

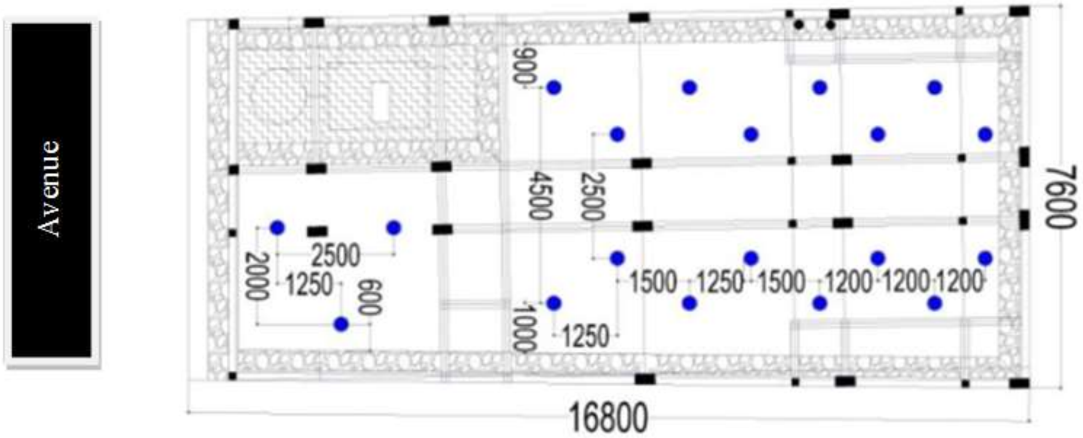

Figure 5. Position of measurement point at 28 positions.

4. RESULTS AND DISCUSSION

4.1. Distribution of air velocity, Relative humidity and Temperature

The characteristic test of cooling at the house using evaporative cooling and vertical ventilation were done by making a square plane of 0.2m ×0.2m with a centre point of the square was measuring point of experiment height of 1.5 m above floor, as illustrated in Figure 6.

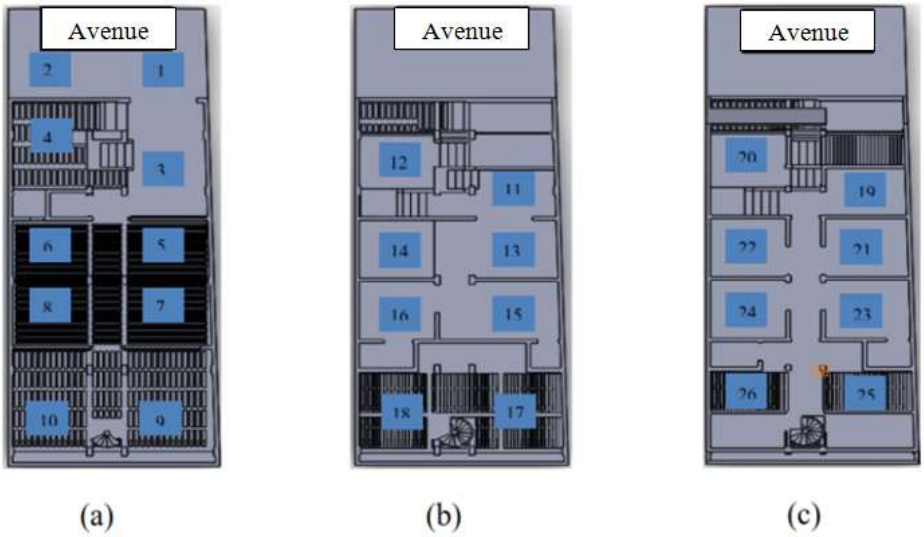

Figure 6. Point position at every floor.

The locations of measurement points 1 and 2 were positioned at the avenue in front of the house, positions 3-10 at the interior house floor 1 (a), points 11-18 at floor 2 (b) and points 19-26 at floor 3 (b), respectively. Meanwhile points 27 and 28 were located at the upper balcony behind the house. The simulation results of air velocity, RH and temperature were gained using CFX calculator function integrated at the ANSYS CFX. All data collected then plotted as appropriate as possible with the experimental data. Air velocity distribution from both experiment and simulation results at different time interval is shown in Figure 7:

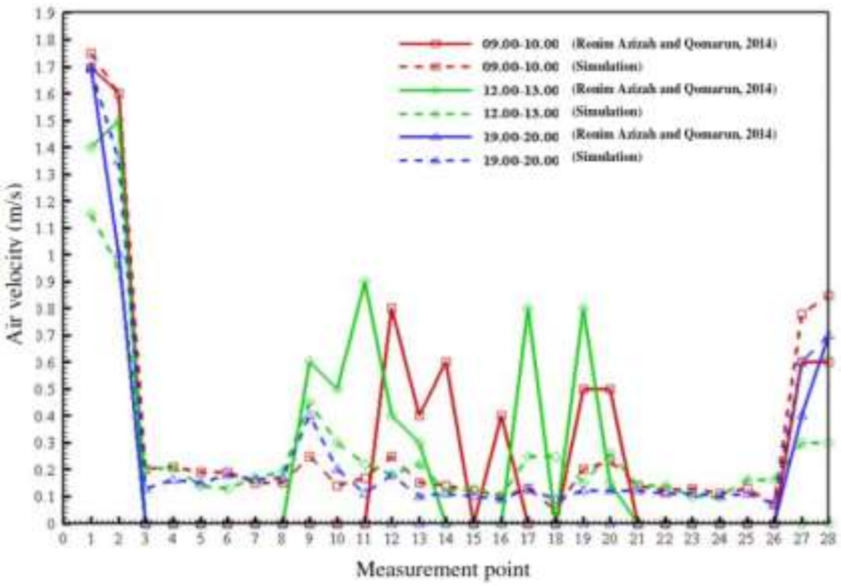

Figure 7. Velocity distribution at 28 measurement points.

Figure.7 shows comparison of velocity distribution at 28 measurement points both of experiment and simulation data, at difference time interval of 09.00-10.00, 12.00-13.00 and 19.00-20.00, respectively. It can be seen that two graphs of experimental and simulation data showed identical chart with the average differences at 09.00-10.00 o'clock of 0.503, at 12.00-13.00 o'clock of 1.427 and at 19.00-20.00 o'clock of 0.161, with the highest velocity for both experiment and simulation were occurred at MP1 and MP2 which is for experiment measurement at a velocity of 1.7m/s, while simulation prediction gives 1.75 m/s.

The similarity was also encountered for both experiment and simulation tend to have constant velocity at MPs 3-8 and 21–26, where experimental measurement having velocity of 0 m/s, whereas, for simulation having velocity of 0.1 – 0.2 m/s. The velocity of 0 m/s at the experimental measurement was predicted due to the insensitivity of equipment when is used at low velocity.

There was also occurred fluctuate velocity at MPs 9-20 for both experiment and simulation, although having difference values. The differences were predicted as the air condition when measurement process was not constant, because measurement process from one point to another point was not conducted at the same time, but in sequence (Azizah R. and Qomarun, 2014). At MPs 27 and 28, the velocity increase for both experimental and simulation by 0.7m/s and 0.8 m/s. RH distribution both experimental results and simulation is shown in Figure 8.

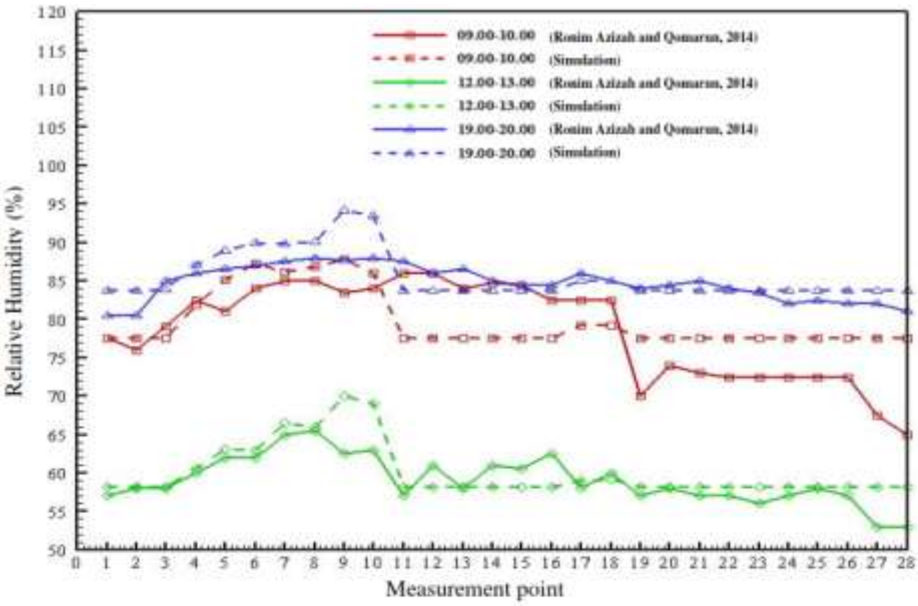

Figure 8. Comparison of RH distribution in % at 28 measurement points.

It can be seen from Figure 8 of relative humidity comparison, that simulation result showed identical with experimental data. At MPs 1–10 (floor 1) from three difference time intervals having nearly same value between simulation result and experimental measurement, it was illustrating that modification with spray water on simulation resulting identical air characteristic very close to the experimental data. Both of two graphs experimental and simulation data showed identical chart with the differences in average at 09.00-10.00 o'clock of 1.080, at 12.00-13.00 o'clock of 1.033 and at 19.00-20.00 o'clock of 0.776. It was difference with MPs 1–10 (floor 1), at MPs 11-18 (floor 2) and MPs 19-28 (floor 3) particularly for time interval simulation of 09.00-10.00 and 12.00-13.00, there were significantly differences between RH and temperature of simulation results with experimental data. The differences were predicted due to ignoring evaporative cooling from water-tree transpiration in the residential home and less detail in defining sun radiation in simulation. The same condition was not occurred at time interval simulation of 19.00 – 20.00, since during that time the RH in the residential home is similarly with environmental condition, therefore, simulation result would be close to the experimental data.

The profile of temperature distribution of simulation and experimental result is shown in figure. 9

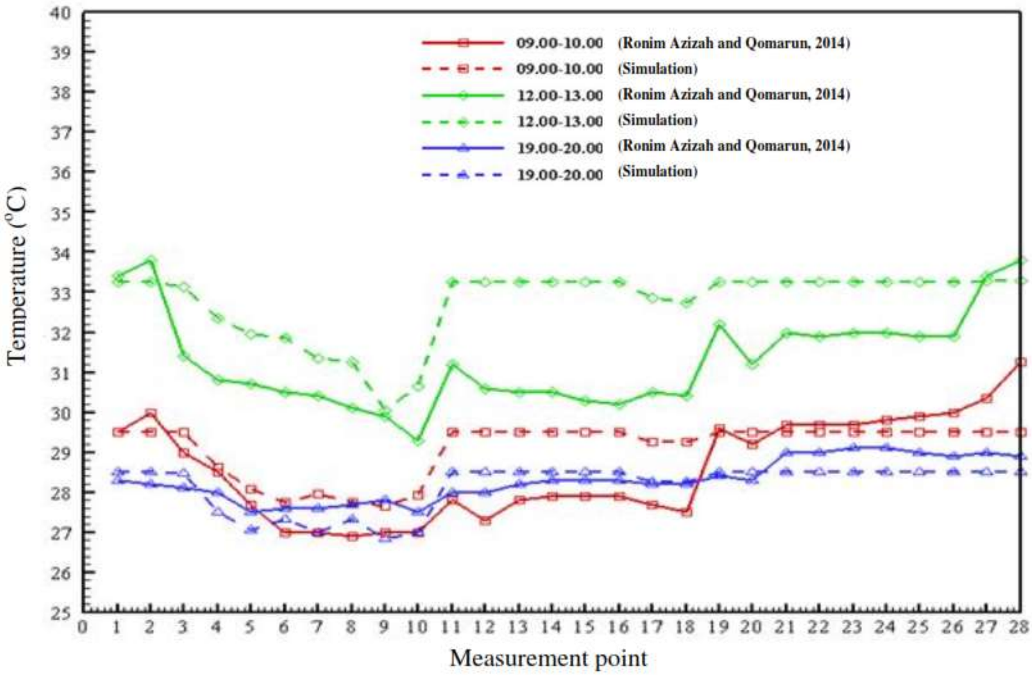

Figure 9. Comparison of Temperature distribution at 28 measurement points.

It can be seen from Figure 9 of temperature comparison that simulation result also showed similar trend with experimental data. At MPs 1–10 (floor 1) from three difference time intervals having nearly same value between simulation result and experimental measurements. Both of two graphs experimental and simulation data showed identical chart with the differences in average at 09.00-10.00 o'clock of 0.503, at 12.00-13.00 o'clock of 1.427and at 19.00-20.00 o'clock of 0.161.

From the simulation results the above, it can be understood that simulation was able to illustrate air circulation and evaporative cooling effect in the residential house, indicated by simulation were generally identical with experimental data.

4.2. Psycrometric Chart versus Comfort Zone

4.2.1. Psycrometric Chart

The psychrometric chart in evaporative cooling process of residential home especially at floor 1, both of at time intervals of 09.00-10.00, 12.00-13.00 also 19.00-20.00 could be seen in Figure10 where at simulation time of 09.00-10.00, incoming ambient air having temperature of 29.5^{o}C with RH of 77.5% and condition after cooling having temperature of 28.1^{o}C at RH of 84.8%. Then, at simulation time of 12.00-13.00, the incoming ambient air having temperature of 33.25^{o}C at RH of 58% and condition after cooling having temperature of 31.57^{o}C at RH of 64.5 %, whereas at time simulation of 19.00-20.00. Incoming ambient air having temperature 28.5 ^{o}C with RH of 83 % and condition after cooling reaching temperature by 27.3 ^{o}C with RH of 89.7 %.

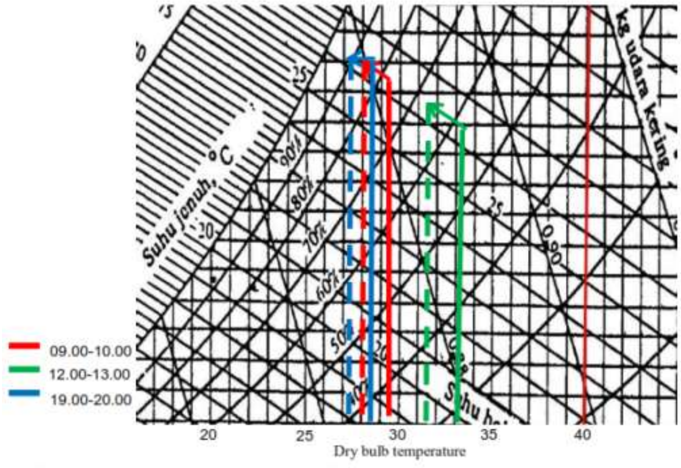

Figure10. Psychrometric chart of evaporative cooling process at 09.00-10.00, 10.00-12.00, 12.00-13.00 and 19.00-20.00.

As indicated in Figure 10, it is believed that simulation for evaporative cooling process at 09.00-10.00 and 12.00-13.00 illustrated of ideal evaporative cooling process since having enthalpy at initial condition and after cooling condition are the same of (h_0=h_1). Whereas, evaporative cooling process at 19.00-20.00, there was less ideal as initial enthalpy were not equal to after cooling condition ($h_0 \neq h_1$).

4.2.2. Comfort Zone

Frick (2007) defined standard thermal comfort for moving air (for the range of air velocity of 0.1 m/s-1.0 m/s), thermal comfort could be achieved at room temperature of 25°C-35°C with RH of 5%-85%. Simulation result at 09.00-10.00 having average velocity of 0.23 m/s with average temperature of 29.1°C and RH of 79.7 %. Then, at simulation time of 12.00-13.00 having average velocity of 0.16 m/s with average temperature of 32.7°C and RH of 60.1%. Meanwhile, at time simulation of 19.00-20.00 having average velocity of 0.18 m/s with average temperature of 28.1°C and RH of 84.5%. Comfort zone at time simulation of 09.00-10.00, 12.00-13.00 and 19.00-20.00 can be seen in Figure 11 as follows.

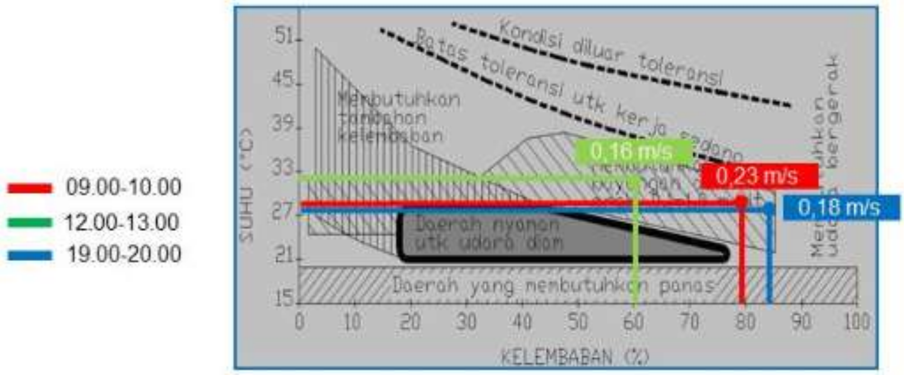

Figure11. Diagram of comfort zone.

From Figure 11, it is concluded that from three-time interval simulation in difference environment conditions, the residential house employing evaporative cooling effect and vertical ventilation give comfortable living for moving air condition (Frick, 2007).

5. CONCLUSION

CFD simulation is able to predict air characteristics in a living house, which employs evaporative cooling and vertical ventilation at three difference time interval operations as:

At the time simulation of 09.00-10.00 at the first floor having average velocity of 0.18 m/s, average RH 84.8%, and average temperature of 28.15^{o}C. At the second floor having average velocity of 0.14 m/s, average RH of 77.95 %, and average temperature of 29.4^{o}C. Meanwhile, at the third floor was indicating average velocity of 0.14 m/s, average RH of 77.5 % and average temperature of 29.5^{o}C.

At time simulation of 12.00-13.00 at the first floor indicating average velocity of 0.19 m/s, average RH of 64.5%, and average temperature of 31.57^{o}C. Whereas, at the second floor, average air velocity was 0.18 m/s, average RH of 58,4%, and average temperature of 33.1^{o}C. While, at the third floor having average air velocity of 0.15 m/s, average RH of 58.2 %, also average temperature of 33.25^{o}C.

At time simulation of19.00-20.00 at the first floor having average velocity of 0.22 m/s, average RH of 89.7 % and average temperature of 27.3^{o}C. Then at the second floor having average air velocity of 0.12 m/s, average RH of 84.06 %, and average temperature of 28.4^{o}C. Meanwhile, at the third floor having average air velocity of 0.11 m/s, average RH of 83.76%, and average temperature of 28.5^{o}C. All three-time simulation was able to give comfortable house of living especially at moving air condition (Frick, 2007).

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