Model Predictive Controller for Air Flow and Heat Transfer in Sample Room

S. Khamput, P. Rattanadecho, and P. Keangin

Abstract—**Energy is necessary for human life. However, various public organizations concern about the limited energy. Therefore, the improving of energy efficiency for building could help the reduction of the energy consumption and costs. The purpose of this study is to investigate the effects of different insulation material, namely brick, polystyrene, stone wool and phenolic foam that applied to sampled room by computational simulation. Three-dimensional model of sample room is presented. The time-dependent fluid dynamic equations coupled with the time-dependent heat transfer equation with diffusion and convection is implemented to predict air flow and heat transfer inside the sample room. The governing equations are solved by using the finite element method (FEM). Computational results of numerical study are compared to results with experimental study. The results indicated that the types of insulation material have the significant effects on the air flow and heat transfer. Furthermore, the stone wool is the best insulation that reduces heat transfer into the room. The obtained results provide useful information on the building designs under a variety of conditions and reduce energy consumption in building.**

Index Terms—**Air flow, computer simulation, heat transfer, insulation materials.**

I. Introduction

Thailand situated in a tropical region and is subjected to hot and humid climate. During the daytime, the solar radiation is the main force that drives heat gain through building envelopes. Consequently, the air-conditioning system is used as the first of energy consumption in building, approximately 60% of this energy consumption [1]. Therefore, the reducing of heat transmission from external wall is the great importance for energy conservation of building.

Thermal insulation is known as one of the most effective ways to reduce the heat transmission rate and energy use in buildings [2]. Many studies were conducted to assess the efficiency of the position and the thickness of the insulation to reduce energy consumption in different climates and different wall orientations. S.A. Al-Sanea *et al*. [3] studied the effects of insulation location on the thermal performance of building envelope walls by numerical methods under steady periodic conditions. The results recommended that the locating insulation on the outer surface of the wall give better thermal performance where the indoor air temperature remains constant. P. Gori *et al*. [4] designed criteria for improving the effectiveness of insulation using the heat transfer matrix approach to solve the one-dimensional model of heat transfer problem through multilayer walls. The results showed that the location of insulating layer on the outer surface of the wall has the highest thermal performance. There are some research studies on investment costs of insulation installation. For example, S. Chirarattananon *et al*. [5] studied the cost effectiveness of the wall insulation of Thailand traditional walls building by comparative energy and economic performance of walls used to enclose air-condition spaces. The comparison of different thicknesses of internal and external wall insulation was investigated. The results indicated that the insulation can help to reduce heat gain to the wall and worth investment. The case study of Irish government's nation grant scheme to encourage energy efficiency retrofitting private housing was presented by A. Byrne et al. [6]. Such case study had methodology that was involved monitored and interviewed data with occupants. The monitored data was measured heat loss through walls between pre- and post-retrofit. It was found that the cavity wall can reduce heat gain through the wall as 21%–66% and the insulated wall as 37%–77%. The survey result from occupants' interviewer given their please with post retrofit because the energy cost was reduce and they have an indoor comfort. However, the previous research have a few studies considered of insulation materials of room design with a three-dimensional model both of experimental study and numerical study, especially a detailed study of the parametric effects for control air flow and heat transfer in sample room. This is because the complicated of the indoor and outdoor environment factors such as solar radiation, convection coefficient, type of supply air, etc. The advantage of topic study will help to predict the air flow and heat transfer inside the room design with saving energy.

This research aims to study the influences of different insulation materials on the variation of air flow and air temperature distribution in sample room. A mathematical model of the flow and heat transfer characteristics of air inside the sample room with insulated wall is expressed completely by the time-dependent fluid dynamic equations coupled with the time-dependent heat transfer equation with diffusion and convection. Governing equations in the study are analyzed by the axisymmetric finite element method (FEM). The benefits of studying in this research can be used as a guideline for design the room with saving energy.

II. Experimental and Numerical

Both experimental and computational studies are carried out to compare the influences of insulation material, i.e. brick,

Manuscript received November 6, 2017; revised May 1, 2018.

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DOI: 10.7763/IJMO.2018.V8.644

polystyrene, stone wool and phenolic foam on the air flow and air temperature distribution inside the sample room. Table I show the thermal properties of insulation material types are used to computation.

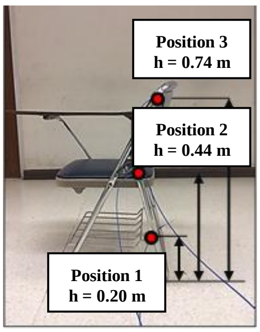
TABLE I: THERMAL PROPERTIES OF INSULATION MATERIAL TYPES USED IN COMPUTATION [7], [8]

Material	Density (kg/m^3)	Specific heat (J/kg.K)	Thermal conductivity (W/m.K)
Brick	20	840	1.75
Polystyrene	24	1250	0.37
Stone wool	24	800	0.045
Phenolic foam	25	1300	0.053

A. Experimental Methodology

The sample room used in the experiment analysis is the classroom R-424 of Faculty of Engineering, Mahidol University. Experimental methodology is carried out in a month of August while the air condition is operated in sampled room. The classroom has outside dimensions of 6.2 m (x) x 8.2 m (y) ×2.8 m (z) and has inside dimensions of 6 m (x) x 8 m (y) × 2.6 m (z). The classroom consists of 1 air conditioning with a cooling capacity of 41,000 BTU per hour and is located in the center of the room. In addition, the classroom comprises of 4 lecture chairs (left-right symmetry in a sample room) and the 12 tubes of 6 W light bulbs. Fig. 1 shows the experimental setup. The sample room used in experimental and the position of the temperature measurement are illustrated in Fig. 1(a) and 1(b), respectively. The measurement of air velocity and air temperature is performed. The initial air velocity is considered as a constant velocity at 0 m/s, while the initial air temperature within the classroom is considered as a constant temperature at 31 ℃. The air velocity and air temperature inside classroom are measured by thermo-anemometer and temperature sensors, respectively. The air temperature inside the sampled room is measured at 6 positions and carried out every 1 min in 30 min for duration [9]. The air temperature data obtained from the experiment are used to compare with the air temperature from the numerical study.

(a)



(b)

Fig. 1. The experimental setup (a) The sample room used in experimental and (b) The position of the temperature measurement.

B. Mathematical Model

The mathematical model in this study is shown in Fig. 2. Fig. 2(a) depicts the physical model of a three-dimensional model of sample room. However, to save the computation time, the axially symmetrical model is used to analyze the air flow and air temperature distribution by numerical utilized, as shown in Fig. 2(b). In order to verify the accuracy of the present model, the simulation results are validated against the experimental results with the same conditions. The convergence test is carried out to identify the suitable numbers of element required. The number of elements where solution is independent of mesh density is found to be 972,301. It is reasonable to confirm that, at this number of element, the accuracy of the simulation results is independent from the number of elements through the calculation process. The Navier-Stokes equation coupled with the heat transfer equation is numerically simulated using COMSOL™ Multi-physics software. The governing equations explaining the air flow within sample room as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \tag{1}$$

Navier-Stokes equation:

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla \cdot \left[-pI + \mu\left(\nabla u + (\nabla u)^T\right) - \frac{2}{3}\mu (\nabla \cdot u) I \right] \tag{2}$$

where ρ is the density (kg/m^3), u is the velocity (m/s), p is the pressure (Pa), μ is the dynamic viscosity (Pa.s) that depends on the physical properties of the fluid, and I is the unit tensor.

The air temperature distribution in the sample room is obtained by solving the conventional heat transport equation in fluid phase where the conduction term and convection term are included.

The governing equations describing the heat transfer phenomenon inside sample room as the following equation:

Heat transfer equation in air:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_P u \cdot \nabla T = \nabla \cdot (k \nabla T) \tag{3}$$

The conduction heat transfer equation is used to solve temperature distribution within wall as given by:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \tag{4}$$

where ρ is the density (kg/m^3), C_p is the specific heat (J/kg.K), k is the thermal conductivity (W/m.K) and T is the temperature ($^\circ$C).

The boundary conditions for air flow and heat transfer analysis reference to Fig. 2(b). The inlet air velocity is measured from supply air condition with constant velocity u = 2.7 m/s.

The initial temperature of indoor air environment is assumed to be constant T_0 = 31 °C at t = 0 s. An axial symmetry boundary is applied at x = 0 for the air flow and heat transfer analysis. The inlet and outlet boundary conditions are applied on the ventilation system for entrance and exit at air condition inside sample room, respectively. The interaction surface between internal wall and external wall is assumed to be constant temperature and is rigid body motion as well as no-slip boundary conditions or air velocity is zero.

Ceiling and floor are assumed to be a thermal insulation boundary condition:

$$-n\cdot(-k\nabla T)=0 \tag{5}$$

The boundary conditions of lamp inside the sample room are prescribed heat flux:

$$-n\cdot(-k\nabla T)=q \tag{6}$$

Heat transfer between the outside environment and wall of sample room are considered as convective boundary condition:

$$-n\cdot(-k\nabla T)=h(T_{ext}-T) \tag{7}$$

In addition, heat transport between the outside environment and glass window of sample room are considered as radiation boundary condition:

$$-n\cdot(-k\nabla T)=\varepsilon\sigma\left(T_{amb}^4-T^4\right) \tag{8}$$

where q is the heat flux (W/m^2), T_{ext} = 32 °C is the external temperature, T_{amb} = 32 °C is the ambient temperature, h is the coefficient convection (W/m^2.K), σ = 5.67×10^{-8} W/m^2.K^4 is the Stefan-Boltzmann constant and ε is the emission (-).

The system of governing equations as well as initial and boundary conditions are solved numerically using the FEM via COMSOL^{TM} Multi-physics.

III. Results and Discussion

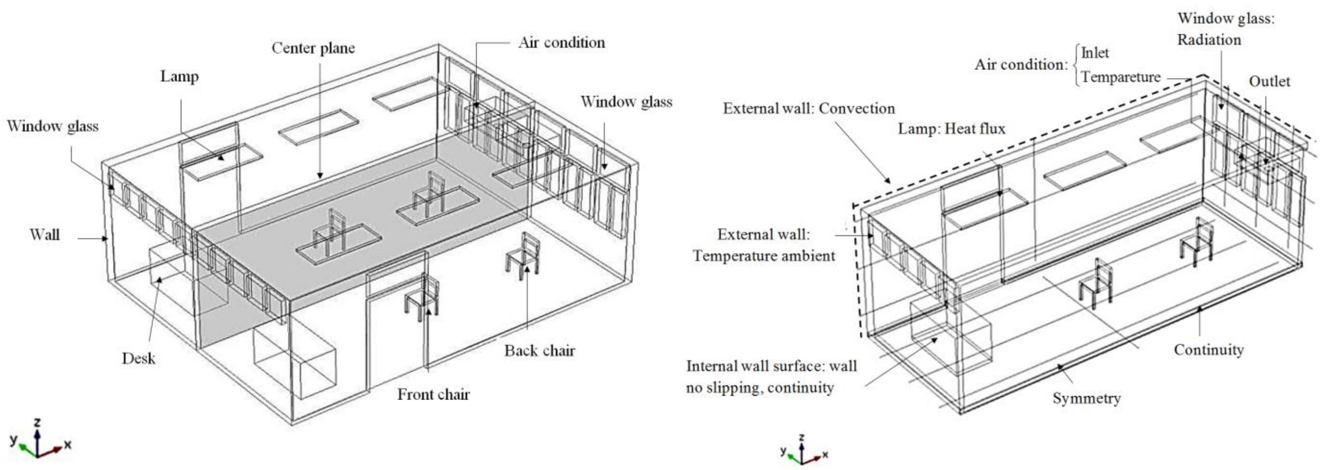
A. Verification of the Model

The accuracy of numerical model is verified by the validation against the experimental under the same geometric model and same conditions. The comparisons of air temperature of simulation results with the experiment results at the position of front chair with the three different positions, which corresponds to Fig. 1(b) and varies with the different times 0 – 30 min as presented in Fig. 3. Figs. 3(a)–(c) show the comparisons of air temperature of simulation results with the experiment results of position 1 (h = 0.20 m), position 2 (h = 0.44 m) and position 3 (h = 0.74 m), respectively. It can be observed that the simulated results are good agreement with the experimental results with similar trends. Certain amount of mismatch between the simulation results and the experiment results is caused by the numerical scheme. Fig. 3 also indicates that the air temperature gradually decreases from the initial temperature and the slightly changes in magnitude happen with each time changes. This comparisons show the accuracy of the present numerical model can precisely represent the phenomena occurring.

B. Effects of Insulation Material

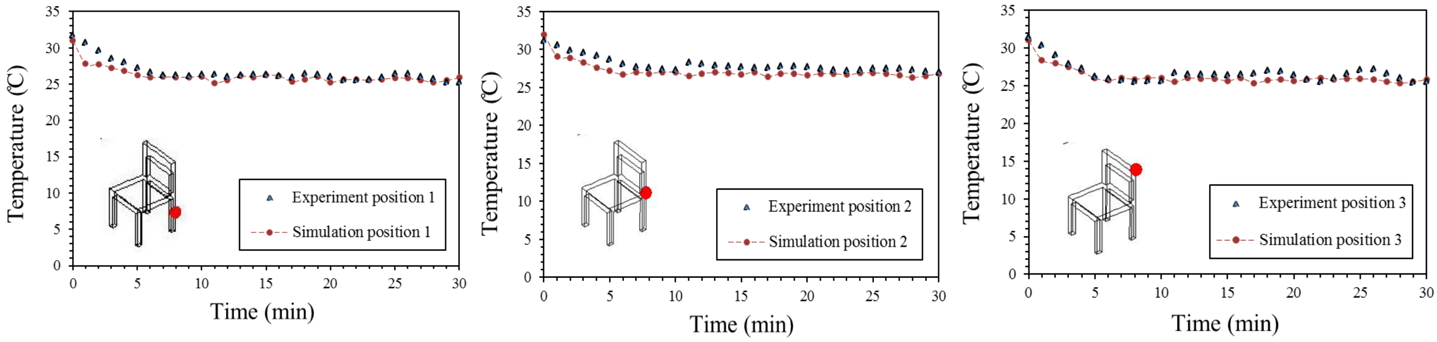
In Fig. 4 demonstrates the time dependent temperature distributing variation by insulating material on brick, polystyrene, stone wool and phenolic foam from different positions including of position 1, 2 and 3. Figs. 4(a)–(c) show the effects of insulation material on the air temperature distribution within sample room for front lecture chair at positions 1, 2 and 3, which corresponds to Fig. 1(b), respectively. Figs. 4(d)–(f) show the effects of the insulation material on the air temperature distribution within sample room for back lecture chair at positions 1, 2 and 3, which corresponds to Fig. 1(b), respectively. The results indicated that the types of insulation material of sample room have a slight effect on the temperature distribution of air inside the sample room. The air temperature distribution of each insulation material will have a similar pattern, it is gradually decreases from the initial temperature and the slightly changes in magnitude happen with each time changes. The higher temperature air is lifted up by the contributing of buoyant force. However, in case of brick has unstable temperature distribution. Considering the effects of the insulation material on the air temperature distribution, in case of using brick the temperature is higher than temperature in case of using phenolic foam, polystyrene, and stone wool, respectively due to the thermal conductivity. The average air temperature inside the sample room in case of using brick, phenolic foam, polystyrene and stone wool are 27.08 °C, 25.40 °C, 25.31 °C and 25.23 °C, respectively. Therefore, it can be concluded that the installation of insulation can reduce the heat gain to the wall. In addition, the results show that the position of the temperature measurement has only a small effect on the air temperature distribution inside the sample room. In case of position 3 is higher temperature than temperature in case of position 2 and position 1, respectively. The lowest position is 1 that affect to no air flowing by.

Figs. 5(a)–(d) show the effects of the insulation material on the air temperature profile within sample room at times of 30 min for brick, polystyrene, stone wool and phenolic foam, respectively. It can be seen that the types of insulation material of sample room have significant effects on the air temperature profile inside the sample room. In case of brick the air temperature is higher than air temperature in case of phenolic foam, polystyrene, and stone wool, respectively corresponds to Fig. 4. The effects of the insulation material on the air flow profile within sample room at times of 30 min for brick, polystyrene, stone wool and phenolic foam are presented in Figs. 6(a)–(d), respectively. The stream line of air flow depicted by arrow implied the air flow from the air condition and return to the outlet. It is found that the air flow is driven by the effect of buoyancy force (natural convection). The flowing air with higher velocity acts as a heat sink and results in dissipates the thermal heat to the surrounding air. It is shown that the air temperature in the vicinity of the air condition is lower air temperature than the surrounding air temperature, resulting in higher air velocity. The average air velocity of front chair at position 1 (h = 0.20 m), is lowest air velocity at 0.080 m/s for brick and the polystyrene is lower than stone wool and phenolic foam is at 0.100 m/s, 0.110 m/s and 0.112 m/s, respectively.



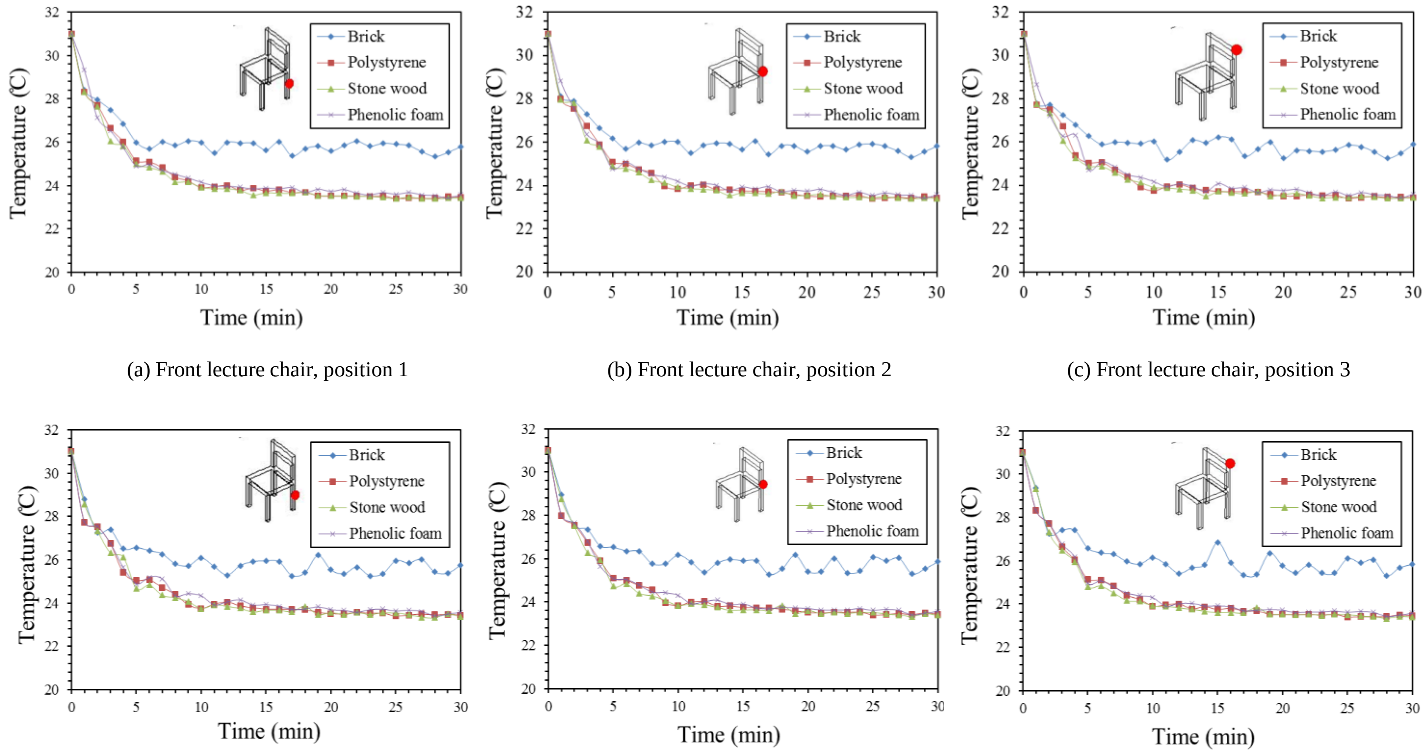
(a) (b)

Fig. 2. The physical model (a) The three-dimensional sample room model and (b) The axially symmetrical sample room model.



(a) (b) (c)

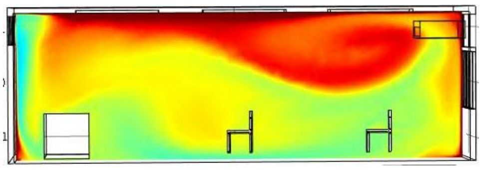
Fig. 3. The comparisons of air temperature from numerical results with the air temperature from experiment results (a) At position 1 (h = 0.20 m), (b) At position 2 (h = 0.44 m) and (c) At position 3 (h = 0.74 m), respectively.



(a) Front lecture chair, position 1 (b) Front lecture chair, position 2 (c) Front lecture chair, position 3

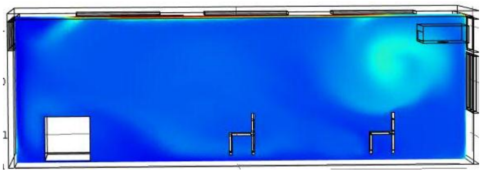
(d) Back lecture chair, position 1 (e) Back lecture chair, position 2 (f) Back lecture chair, position 3

Fig. 4. The effects of the insulation material on the air temperature distribution within sample room at the position of front and back lecture chairs (a) Front lecture chair at position 1(b) Front lecture chair at position 2 (c) Front lecture chair at position 3 (d) Back lecture chair at position 1(e) Back lecture chair at position 2 and (f) Back lecture chair at position 3.

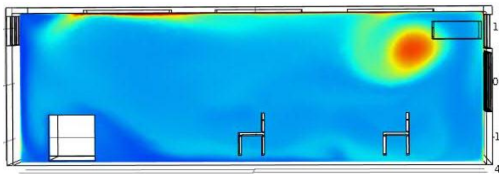


(a) Air temperature profile using brick at t = 30 min

(b) Air temperature profile using polystyrene at t = 30 min



(c) Air temperature profile using stone wool at t = 30 min



(d) Air temperature profile using phenolic foam at t = 30 min

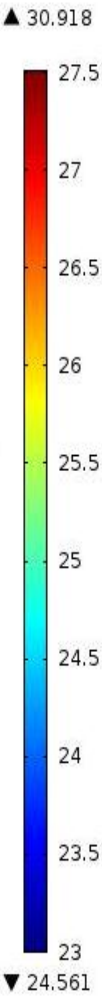
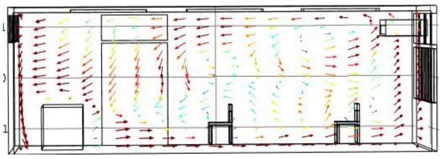
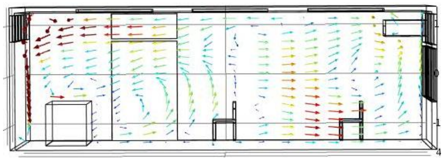


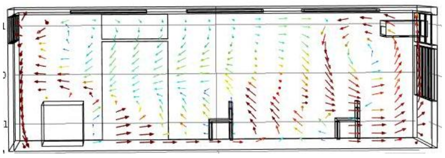
Fig. 5. Air temperature profile inside sample room using different insulation materials.



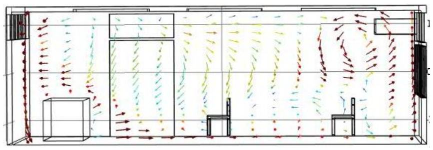
(a) Air velocity profile using brick at t = 30 min



(b) Air velocity profile using polystyrene at t = 30 min



(c) Air velocity profile using stone wool at t = 30 min



(d) Air velocity profile using phenolic foam at t = 30 min

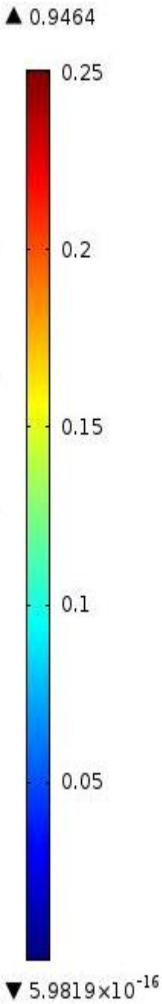


Fig. 6. Air velocity profile inside sample room using different insulation materials.

IV. Conclusions

The influences of thermal insulation material on air flow and air temperature distribution in the sample room is investigated by using three-dimensional numerical model. The air temperature results obtained from the numerical study is validated with the air temperature results obtained from the experimental study. The results showed that the air temperature distributions of all sampled cases are good agreement compared to experimental measurement. The differences of insulation material, namely brick, polystyrene, stone wool and phenolic foam are studied. The effects of insulation material are the same for the air temperature distribution but with slightly different amplitudes for each case. In case of using polystyrene, stone wool and phenolic foam has only a small effect on the air temperature distribution, but a clear effect on the air temperature distribution in case of using brick. The transient calculation points out the highest temperature occurred in case of brick, phenolic foam, polystyrene, and stone wool, respectively. Moreover, the slightly velocity variation is found in all cases. The air velocity and air temperature are related as direct variation. Finally, the outcome of this research can help guide the choice of insulation types and provide a basis for energy design of various types of buildings.

Acknowledgment

The authors would like to acknowledge the financial support from the Faculty of Graduate Studies, Mahidol University and Department of Mechanical Engineering, Faculty of Engineering, Mahidol University.

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