Thermal Recirculation and Efficiency of Phenolic Resin as Building Insulation

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ABSTRACT: The objective of this research is to develop a comfortable living environment with energy-saving features. Two buildings insulated with phenolic resins were constructed according to experimental design to study variations of outdoor and indoor temperatures. The CFD program is used to simulate the large-scale environmental flow field analyses. Results of CFD simulation carried out for the five time intervals of a day show that (1) air current assists in carrying away heat from the wall surface, the indoor temperature drops faster and the indoor air flow becomes turbulent when the window is opened; (2) when the window is closed, the indoor air flow near the window varies the most; (3) phenoic resin insulation has good thermal property.

INTRODUCTION

Most buildings with close environment are not capable of dissipating properly the thermal heat input; hence, the heat is accumulated to increase the building indoor temperature. Auxiliary air conditioning is needed in modern buildings to maintain a comfortable living or working environment at the cost of energy consumption. How to manage a comfortable environment with the minimum consumption of energy is a major concern and research topic for many nations [1–5]. Hence, heat preservation and insulation are discussed so that the thermal transport from outside environment into a closed building or environment can be reduced to alleviate the air conditioning loadings [6,7]. During ancient times, leaves and thatch were used as natural insulating materials to insulate buildings. In the 20th century, the modern science and technology leads to the development of many insulating materials with high thermal efficiencies including light-weight formed materials, materials inlayed with air pockets, and reflective materials. Modern building emphasizes the use of materials that is aesthetically natural, comfortable and healthy. In addition to providing effective insulation, the insulating material must be light-weight with strength, easy to process, durable, aesthetic, comfortable, healthy, easy to clean, and resistant to moisture and microbial growth. Other energy and pollution related features of the construction material include requiring low energy to produce, with low pollution potential and environmentally friendly. The new phenolic insulation material used in this research is environmentally friendly with high economic value; it is low in toxicity and efficient in insulation so that it can be considered as a green construction material [8–10].

In order to understand whether the phenolic resin is suitable for building insulation material, it is used to insulate the experimental building for monitoring outdoor and indoor temperatures across the roof and the walls on the four sides (east, south, west and north) to evaluate the insulation efficiency of the phenolic resin as building insulation material. The experimental results show that during summer, phenolic plate has obvious insulation effect of reducing 5–10°C whereas during winter under northeastern monsoon, the temperature difference across the building wall is 4–7°C indicating the characteristics of phenolic plate to insulate against low temperature [11]. The computational fluid dynamics (CFD) program is used to simulate the large-scale environmental flow field analyses so that more realistic simulation results with fewer errors can be obtained. The CFD to simulate the building isolated with phenolic resin based on the experimental monitoring results obtained in previous years. The results thus obtained

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will provide valuable references to future relative base design, building construction, and landscape.

**METHODOLOGY**

During the first year of the research, phenolic resin was used to construct an experimental building in order to understand whether the phenolic resin is applicable for constructing a building to provide comfort living conditions with less energy consumptions. Two phenolic resin-insulated experimental buildings with 30 monitoring points as shown in Figure 1 were constructed to study thermal transportation and temperature variations.

The experimental results were used to identify parameters for conducting the simulation on solar radiation, thermal transportation between outdoor and indoor across phenolic resin board, and temperature variations using the CFD program. The computer model is shown in Figure 2. The underlying equation for this multiphysics CFD modeling in building envelopes is the energy equation shown in Equations (1)–(3). The energy equation allows considering the effect of all of the following heat phenomena: convection in fluid, conduction in solids, thermal (solar) radiation, and external heat gains.

\[
\rho \frac{\partial \vec{V}}{\partial t} + \rho (\vec{V} \cdot \nabla)\vec{V} = -\nabla P + \rho \vec{g} + \mu \nabla^2 \vec{V} \tag{1}
\]

\[
\rho C_p \frac{\partial T}{\partial t} + (\vec{V} \cdot \nabla)\rho C_p T = \nabla \cdot (k \nabla T) + \mu \Phi + \dot{q} \tag{2}
\]

\[
\rho = \frac{p_{op} + p}{R M_w T} \tag{3}
\]

Where:
- \(T\) = Temperature
- \(\rho\) = Density
- \(C_p\) = Specific Heat
- \(q\) = Heat source (mean solar radiation)
- \(R\) = Gas constant
- \(M_w\) = molecular weight of gas
- \(-\Delta P\) = is the pressure force
- \(\rho \vec{g}\) = is the gravity force
- \(\mu \nabla^2 \vec{V}\) = is the shearing force
- \(\nabla \cdot (k \nabla T)\) = is the conduction dissipation
- \(\mu \Phi\) = is the Viscous dissipation
- \(\dot{q}\) = is the Heat generation

*Figure 1. Buildings equipped with phenolic resin insulation.*

*Figure 2. Simulated model of the experimental building.*
Weather variables (major influencing factors include: air temperature, air density, wind velocity etc.) considerably influence the hydrothermal performance of a building envelope. In site planning, buildings can then be reasonably positioned based on the analysis result of the wind environment, while other factors such as day lighting, noise, building coverage, height, orientation, spacing and configuration are addressed as well [12,13]. Therefore it is essential to incorporate these variables into this simulation methodology. Air temperature should not be the only parameter used to define the thermal climate, but indeed it is the most commonly used. In this paper the operative temperature [Equation (4)] is calculated, which includes the ambient air temperature ($T_a$), air velocity ($v$) and the mean radiation temperature [Equation (5)] that is as a function of the radiation intensity from each surface.

\[
T_{op} = \begin{cases} 
(M.R.T + T_a \sqrt{10v})/(1 + \sqrt{10v}) & (v \geq 0.1 \text{ m/s}) \\
(M.R.T + T_a)/2 & (v < 0.1 \text{ m/s}) 
\end{cases}
\]

\[
M.R.T. = \left( \frac{l_{rad} \cdot \pi}{\sigma} \right)^{0.25}
\]

Where:

- $M.R.T.$ = Means radiation temperature ($T_a$)
- $T_a$ = Ambient air temperature ($^\circ$C)
- $T_{op}$ = Operative temperature ($^\circ$C)
- $v$ = Velocity (m/s)
- $\sigma$ = Stefan Boltzmann constant (kg/(s3 K4))
- $l_{rad}$ = radiation intensity (W/(m² sr))

The solar variables such as the sun direction vectors, sunshine fraction, and direct and diffuse solar irradiation necessary for the solar ray tracing algorithm computations are then calculated. The energy equation is show as Equations (6)–(8) [15].

\[
E_{total} = E_{direct} + E_{diffuse, solar} + E_{reflect, ground}
\]

\[
E_{d, solar} = CE_{direct} \frac{1 + \cos \epsilon}{2}
\]

\[
E_{r, ground} = E_{direct} (C + \sin \beta) \rho_s \frac{1 + \cos \epsilon}{2}
\]

Where:

- $E_{total}$ = total solar radiation
- $E_{direct}$ = normal direct solar irradiation
- $E_{diffuse}$ = total diffuse irradiation
- $E_{d, solar}$ = diffuse solar irradiation
- $E_{r, ground}$ = ground reflected solar irradiation

The simulation was carried out based on various grids to perform grid independence test. First, one point in the model was selected as the reference point for selecting points with various heights to perform grid test analyses with the results shown in Figure 3. Seven sets of various grid numbers were evaluated for the grid range from 20w cells to 400w cells. The grid of 250w cells shows no tendency of diffusion or convergence; i.e. the analysis results carry no significant variations so that stable simulation and good analysis results are obtained (Figure 4). Hence, the grid of 250w cells was used for performing the subsequent simulation based on conditions of the actual site with comparisons of actually monitored experimental data and computer monitoring results for model calibration. The weather conditions for July (summer) in Taichung (Taiwan) were used for simulating the atmospheric space for evaluating the overall building indoor and outdoor thermal environments.

RESULTS AND DISCUSSIONS

Results of simulation on variations of the outdoor and indoor temperatures using data collected with the experimental building insulated with phenolic resin are shown in Figure 5 (window closed) and Figure 6 (windows opened). Under similar conditions, when the ambient wind speed is not high, the room with windows closed has more uniform temperature distribution than room with windows opened that reveals the insulating characteristics of phenolic resins. At 8:00 A.M., the east-side wall is exposed to solar irradiation; its temperature
gradually increases. At noon, the sun is directly over the building so that heat comes directly from the roof top. At 2:00 P.M., the west-side wall is exposed to solar irradiation, and breeze enters the building through the east-side window to carry some heat away from the wall. Hence, opening the window causes the room temperature to drop fast. The simulation results for the period between 8:00 A.M. and 10:00 A.M. indicate that the opened window causes the room temperature to rise. Additionally, when the window is opened, the heat comes from a fixed source but the movement of indoor air current leads to more uniform spatial temperature distribution but higher room temperature.

Results of flow analyses along the north-south directions are indicated in Figure 7 for closed window and Figure 8 for opened window. The window is located on the east-side wall; when the sun is above the horizon at a certain angle of inclination, a small floor area is exposed to the incident solar irradiation through the window. Hence, the simulated results for the period between 8:00 A.M. and 10:00 A.M. show a region of relatively higher temperature adjacent to the hot floor area. With the sun rises further, this floor area will gradually move from the center of the building toward the window.

When the window of the phenolic resin insulated building is closed, heat is easily transmitted through the window glass panes into the building. Hence, the area surrounding the windows experiences the generation of more vigorous speed field during all time intervals starting 8:00 A.M.. Figure 7 shows that the east-side wall is exposed to heat at 8:00 A.M., but the temperature is not obvious so that the speed field is weak. During other time intervals, the window shows obvious vigorous heat exchange; the speed field shows the direction from the east-wall window toward the west-side wall. After reaching the wall, it is diffused toward the room and the ground.

Simulation results for the insulated building with window opened (Figure 8) show that after entering the building through window, the air current diffuses to all directions until hitting the boundary wall; it is then reflected from the wall to form turbulent current. Because the experimental building has a single window, after the formation of turbulent air current, some air current may also flow out of the building. Hence, air flows of different directions, i.e. flowing into and out of the room, near the window cause weaken air current flowing into the building and poor indoor air circulation that indirectly affect the building heat dissipation.
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Figure 5. Simulated Room Temperature for Window Closed.

Figure 6. Simulated Room Temperature for Window Opened.
Figure 7. Simulated Variations of Air flow for Closed Window (North-South Direction).

Figure 8. Simulated Variations of Air flow for Opened Window (North-South Direction).
Figures 9–13 show temperature distributions during the four time intervals between 8:00 A.M. and 4:00 P.M. on the roof and outside surface of the wall for closed window whereas Figures 14–18 show those for opened window. Among the five time intervals, at 8:00 A.M., the wall temperature is generally the lowest, and the east-side wall surface temperature is the highest among walls of other directions because the east-side wall is subject directly to the sun rising in the south-east direction. During the same time interval, the roof temperature rises gradually. At 10:00 A.M., the sun rises higher, the east-side wall is under the roof shadow, its heated surface is thus reduced but the temperature rises for the roof and the wall on other sides. At 12:00 noon, the sun is at the apex, and the building shadow is the smallest so that the indoor heat mainly comes from the roof.

At 2:00 P.M., the west-side wall is subject to solar irradiation so that its temperature rises whereas the roof temperature rises continuously to reach the highest level of 55°C and then gradually decreases. When the sun moves to the 4:00 P.M. position, the area exposed to solar irradiation for the west-side wall increases, and the east-side roof temperature decreases. Because the sun rises from southwest to move toward northwest, the north-side wall surface experiences faster temperature decrease than the east-side and south-side walls.

The two experimental buildings have similar appearance, dimensions and features; they are subject to similar environmental and heating condition. The influence of window is the greatest because the window is the largest transparent structure in the experimental building. The solar radiation can easily penetrate the transparent window to bring the solar radiation heat into the building because the traditional window has lower heat transmittance of 6.40 W/(m²·K) than solid wall. Results of the model simulation for the building with opened window show that the outside wall surface temperature is always higher than indoor room
Figure 13. Simulated 4:00 P.M. Wall Surface Temperature (Window Closed).

Figure 14. Simulated 8:00 A.M. Wall Surface Temperature (Window Opened).

Figure 15. Simulated 10:00 P.M. Wall Surface Temperature (Window Opened).

Figure 16. Simulated 12:00 noon Wall Surface Temperature (Window Opened).

Figure 17. Simulated 2:00 P.M. Wall Surface Temperature (Window Opened).

Figure 18. Simulated 4:00 P.M. Wall Surface Temperature (Window Opened).
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Temperature. Hence, when the building is subject to poor ventilation or weak wind speed, heat can easily be transmitted indoors but cannot be dissipated easily so that the indoor temperature is raised.

Figures 19–23 shows the simulation of outdoor air field in this region and the resulting indoor air field; Figures 24–28 show the simulation results on the diffusions for both building sides and roof. Under full sunshine without shading, the building and surrounding ground show different temperature at various times; the temperatures are the highest at 12:00 noon and next highest at 2:00 P.M. Simulation of the larger environment shows that air field influences the temperature variations for the building and the surrounding ground. Air current will bring heat away from the wall surface and ground so that the building north wall temperature has a tendency of being relatively low under the large environment. The building shade also causes temperature differences between wall surface and surrounding ground in addition to indicating the angle of solar ir...
Figure 23. The 4:00 P.M. air field analyses for outdoor environment (window closed).

Figure 24. The 8:00 A.M. air field analyses for outdoor environment (window opened).

Figure 25. The 10:00 A.M. air field analyses for outdoor environment (window closed).

Figure 26. The 12:00 P.M. air field analyses for outdoor environment (window closed).

Figure 27. The 2:00 P.M. air field analyses for outdoor environment (window closed).

Figure 28. The 4:00 P.M. air field analyses for outdoor environment (window closed).
Frequently closing the window may affect the building permeability and aesthetic appearance, glass pane with good insulation property can be used to reduce solar irradiation and absorbance.

CONCLUSIONS

Mimicking nature to improve building design for reducing energy consumption, environmental pollution, and urban heat island effect has been seriously conserved in recent years. Improving building design to provide a comfortable indoor living environment without consuming excess energy is an important issue to energy-thirsty Taiwan that is located in subtropical region with hot and humid summer. In this research, the thermal insulation behavior of phenolic resin used as building insulation is studied using laboratory buildings insulated with phenolic resin. A computer model is developed using the CFD software to simulate the building thermal behavior. The solar irradiation, building, and the ambient and indoor thermal environments were simulated using the experimental data obtained earlier to result in more realistic simulated conclusions without significant errors.

Results of CFD simulation carried out for the five time intervals of a day show that air current assists in carrying away heat from the wall surface, and the indoor temperature drops faster when the window is opened. Temperature variations between 8:00 A.M. and 10:00 A.M. reveal that opening window will raise the indoor temperature during this time period. Results of simulating the indoor air flow show that when the window is closed, the indoor air flow near the window varies the most; the air speed velocity field is from the east-side wall to the west-side wall. When the window is opened, the indoor air flow becomes turbulent. After entering the room through the window, the air diffuses in all directions, and the speed field is compensable or weakened by air flow of the opposite direction leading to poor indoor ventilation. Simulation of the larger environment indicates that window is an important factor to influence the indoor thermal behavior. Phenolic resin insulation has good thermal property; if it is applied in cope with other means such as shading or improving window constructing materials, the room temperature will be effectively reduced. The environmental air flow will effectively assist in removing heat from the wall surface and floor. Under the experimental conditions, the daytime outdoor temperature is higher than indoor temperature so that ventilation can only be applied during nighttime when the outside temperature becomes lower. This study offers quantitative scientific data to confirm a common practice for lowering indoor temperature. Results of this environmental air flow analysis will be valuable quantitative information to be referenced by engineers and planners for future base design or landscape design of energy-efficient green buildings.

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