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Numerical Investigation Of Heat And Energy Transfer In Traditional Balinese Buildings

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Abstrak

Perpindahan panas dan energi di sekitar sekumpulan bangunan – bangunan berarsitektur tradisional Bali sangatlah kompleks dan sulit untuk dinyatakan dengan menggunakan suatu model bangunan yang terisolasi (dengan menggunkan kondisi simetris). Model dengan skal penuh dari bangunan tradisional dikaji dengan menggunakan metoda elemen hingga, untuk menguji pengaruh dari jenis atap terhadap perpindahan panas dan energinya. Model turbulensi dengan k-ε standar serta menggunakan harga k-ε yang rendah digunakan dalam pengujian ini namun mengkombinasikannya dengan multi-blocks grids, dalam rangka mengurangi kelebihan estimasi produksi dari energi kinetik turbulensi akibat pemakaian model turbulensi dengan k-ε standar.

Kata Kunci: *Elemen Hingga, bangunan tradisional Bali, aliran turbulen, perpindahan energi*

Abstract

The heat and energy transfer around a cluster of traditional Balinese buildings is extremely complicated and difficult to determine by modeling an isolated building (e.g. via symmetry conditions). Full scale models of traditional buildings have been investigated by using numerical method based on the finite element method, to assess the effects of roof type on heat and energy transfer. A standard k-ε model is adopted with low values of k and ε combined with multi-blocks grids, in order to reduce the over-estimation of the production term of the turbulent kinetic energy in standard k-ε turbulence models.

Keywords *Finite elements, traditional Balinese buildings, turbulent flow, heat transfer*

1. Introduction

Natural ventilation proves to be a realistic alternative for energy conservation and thermal comfort of building occupants in a tropical country with a warm climate and high relative humidity. This investigation is started with a hypothesis that there is a relation between roof type of traditional Balinese buildings with energy conservation and thermal comfort of occupants. The study aims to reduce the cooling loads of buildings and improve the indoor thermal comfort by modifying the roof type of buildings, therefore, the effects of orientation, infiltration, ventilation and size of buildings are not considered.

2. Physical description and mathematical model

Typical traditional Balinese buildings are depicted in Figure 1(a). Four types of roof are used in the present study, as shown in Figure 1(b). Since the flow region is unbounded, an upper truncation boundary is artificially placed at a height of 2.25 H, where H is the height of the houses' eaves (Figure 2); this value was arrived at by trial and error.

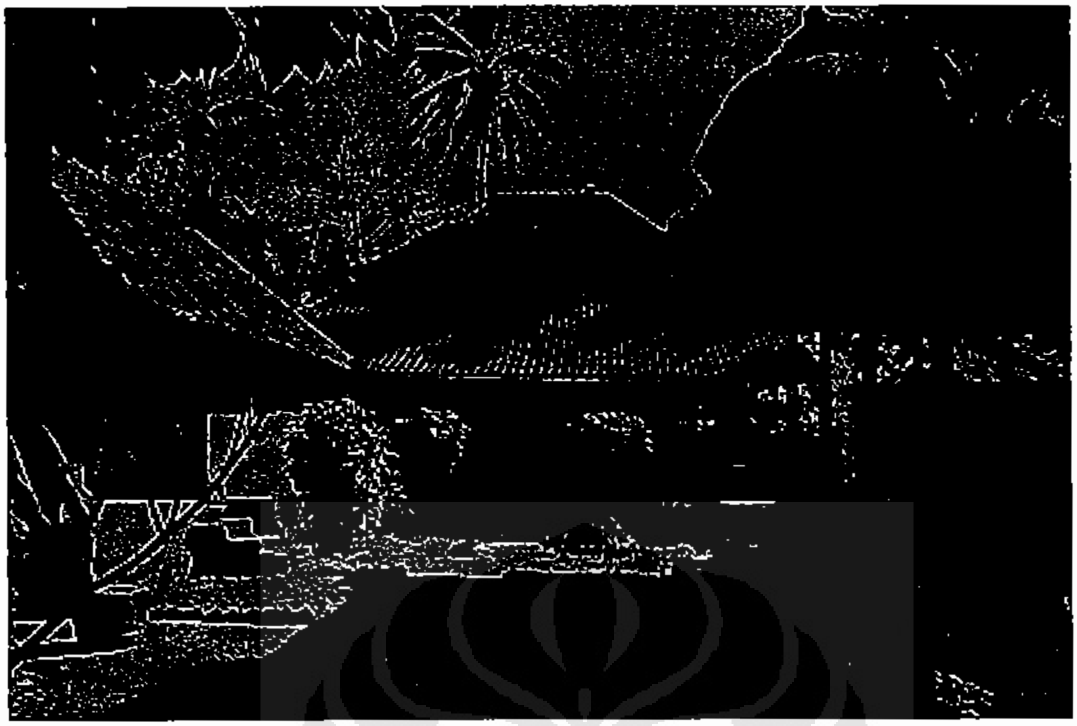
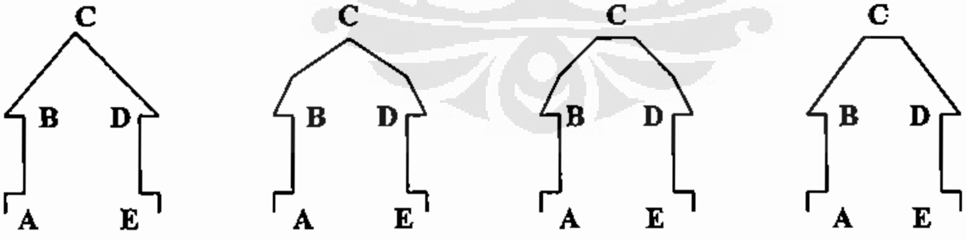
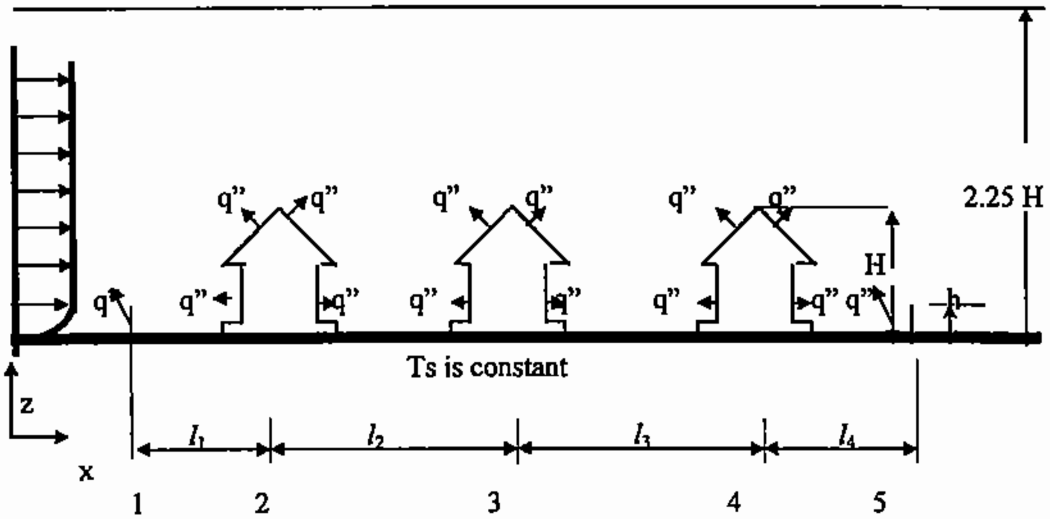


Figure 1(a). Traditional Balinese buildings



Model 1 **Model 2** **Model 3** **Model 4**

Figure 1(b). Geometry of roof



1 = front fence
2 = first house
3 = second house
4 = third house
5 = back fence
l_1 = distance between the front fence and first house
l_2 = distance between first and second houses
l_3 = distance between second and third houses
l_4 = distance between third house and the back fence
H = height of the houses
q" = heat flux on the surface
T_s = ground temperature

Figure 2. Geometry of the problem and boundary conditions for computations

This height was also examined in order to ensure that the imposed boundary conditions are correct. Boundary conditions appertaining to fully developed flow are imposed at the inlet. A uniform heat flux q'' is applied at the houses and fences, so that thermal stratification is established in the field. Since temperature changes on the ground are mainly caused by heat conduction, a uniform temperature T_s is applied on the ground. This value was measured daily at the peak time, in the dry season. Surface roughness of the walls is also considered in the modeling.

The following assumptions and conditions are introduced:

1. The region of the atmospheric boundary layer from the ground up to 500 m above the Earth's surface is considered in this simulation. The surface boundary layer at an altitude 10 m is supposed to be the layer of constant vertical momentum, heat and mass fluxes, then Monin-Obukhov's similarity theory is applied [1].
2. The horizontal distance of 100 m is considered in this simulation.
3. Radiation heat transfer is not considered.
4. The atmosphere is assumed to be in hydrostatic equilibrium. The Boussinesq approximation is adopted [2].

2.1. Boundary conditions

The boundary conditions for the atmospheric boundary layer model are those for a homogeneous boundary layer with the following characteristics:

(a) Inlet

The boundary conditions for the inlet velocity are fixed with the profile $\frac{\overline{u_y}}{\overline{u_{10m}}} = \frac{\log(y/y_0)}{\log(10/y_0)}$, where $\overline{u_y}$ and $\overline{u_{10m}}$ are the mean velocities at height y and 10 m, respectively, y_0 is a surface roughness length of 0.010 m for a cut grass fetch, and $v = w = 0$ [3]. The turbulent intensity was evaluated to be 6.2% according to Davenport's terrain roughness classification number 4 for a suburban terrain [4], and the inlet temperature (T_0) is 301 K.

The shear stress is constant and given by

$$(\mu_l + \mu_t)\frac{\partial u}{\partial y} = \tau_w = \rho u_\tau^2 \qquad (1)$$

where μ_l, μ_t, τ_w, ρ and u_τ are laminar viscosity, turbulent viscosity, solid surface shear stress, density and friction velocity, respectively. The turbulent kinetic energy k and its dissipation rate ε satisfy their respective conservation equations which reduce to

$$\frac{\partial}{\partial z}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial y}\right] + \mu_t G_k - \rho\varepsilon = 0 \qquad (2)$$

$$\frac{\partial}{\partial z}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial y}\right] + C_1\mu_t G_k\frac{\varepsilon}{k} - C_2\rho\frac{\varepsilon^2}{k} = 0$$

where

$$G_k = \left[\frac{\partial u}{\partial y}\right]^2 \qquad (3)$$

$\sigma_k, \sigma_\varepsilon, C_1$ and C_2 are constants of the model, with $\sigma_k = 1.0, \sigma_\varepsilon = 1.3, C_1 = 1.44$ and C_2=1.92.

The above equations are satisfied by using

$$u = \frac{u_\tau}{K}\ln\left[\frac{y + y_0}{y_0}\right] \qquad (4)$$

$$K = \frac{u_\tau^2}{\sqrt{C_\mu}} \qquad (5)$$

$$\varepsilon = \frac{u_\tau^3}{K(y + y_0)} \qquad (6)$$

where K is von Karman's constant ($\cong 0.41$) and $C_\mu = 0.09$.

(b) Solid boundaries

Velocity is zero on the ground, the fence and the buildings. Temperature is constant and equal to 305 K on the ground. Heat fluxes were assumed to be constant but having different values along the fences, the building walls, ceiling and roof; these values are estimated from the measured peak-time temperatures, and change according to building location and orientation. The wall studied here is well insulated and no heat losses exist due to the temperature differences between the outer and inner faces. The heat flux at a wall surface specifies that the thermal boundary condition is only caused by forced convection. The surface roughness (*e*) varies between 0.05% and 0.10% of the houses' height (*H*), and is applied for all wall surfaces. On the truncated walls and building surfaces, the wall treatment is a combination of logarithmic and no-slip boundary conditions.

(c) Outlet

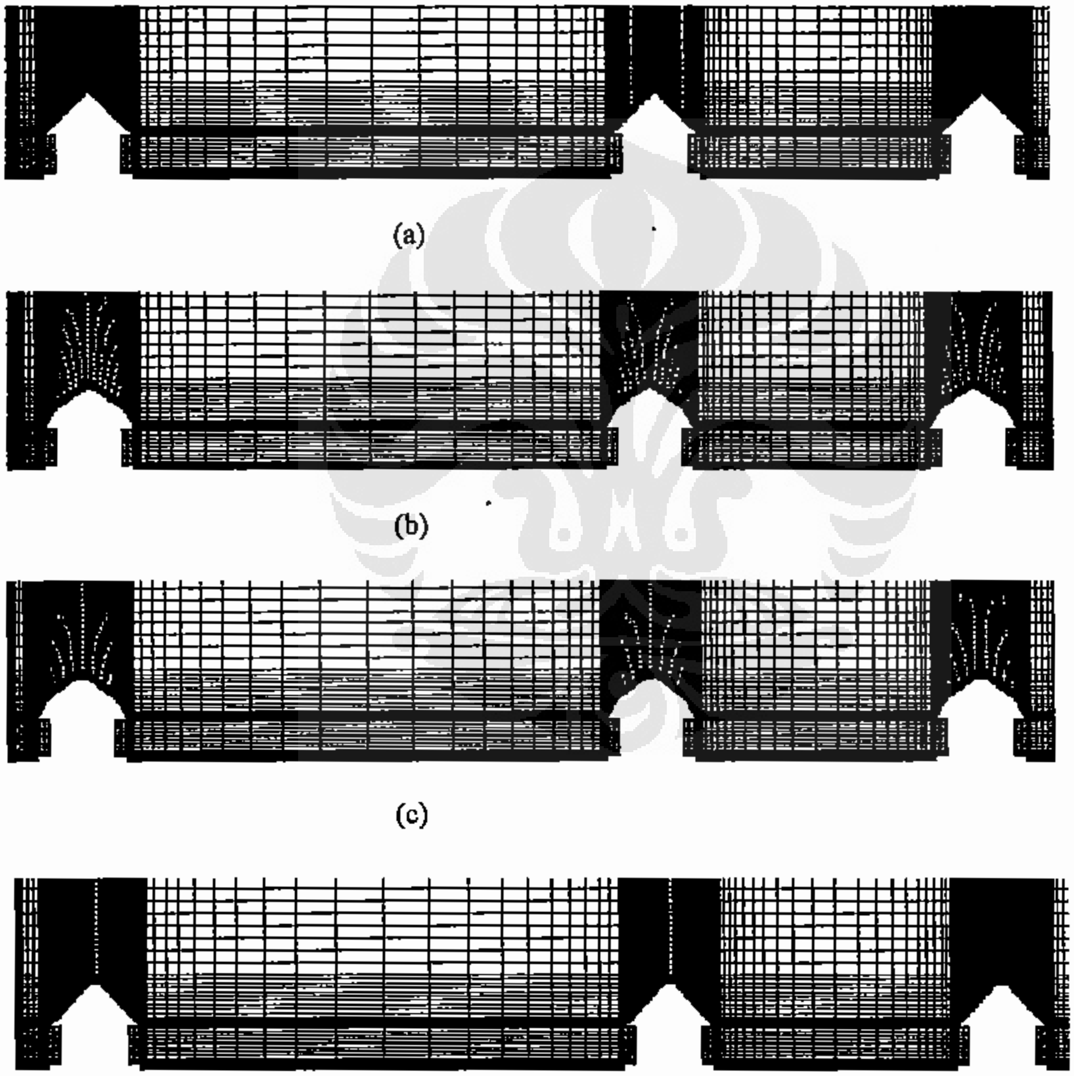
At the outlet, homogenous Neumann boundary conditions are applied for all variables.

2.2. Numerical procedures

The conservation equations are written in terms of the primitive variables, with pressure removed through a penalty function formulation. The turbulence model is a standard $k - \varepsilon$ with a logarithmic-law near-wall closure scheme. The set of differential equations is solved iteratively using Picard's iteration [5], with successive relaxation point iteration with an under-relaxation parameter of 0.7 for each cycle. The convergence criterion requires that the sum of residuals over the whole domain should be less than a small specified tolerance (10^{-6}).

3. Grid-independence tests

Grid-independence tests play an important role on numerical simulations, especially if the wall shear stresses need to be calculated accurately [6 and 7]. Simulations were started by using a coarse mesh to get an idea of the overall features of the solution. The grid was then refined in stages until no significant differences of results occurred between successive grid refinement stages, the so-called grid-independent results. The chosen grids were non-uniform and regular. Multiple blocks have been used in order to reduce the truncation error. By using the multi-blocks system and a combination of uniform and non-uniform grids, the grids used in the present study are considered to be suitable for a complex building configuration.



(a)

(b)

(c)

(d)

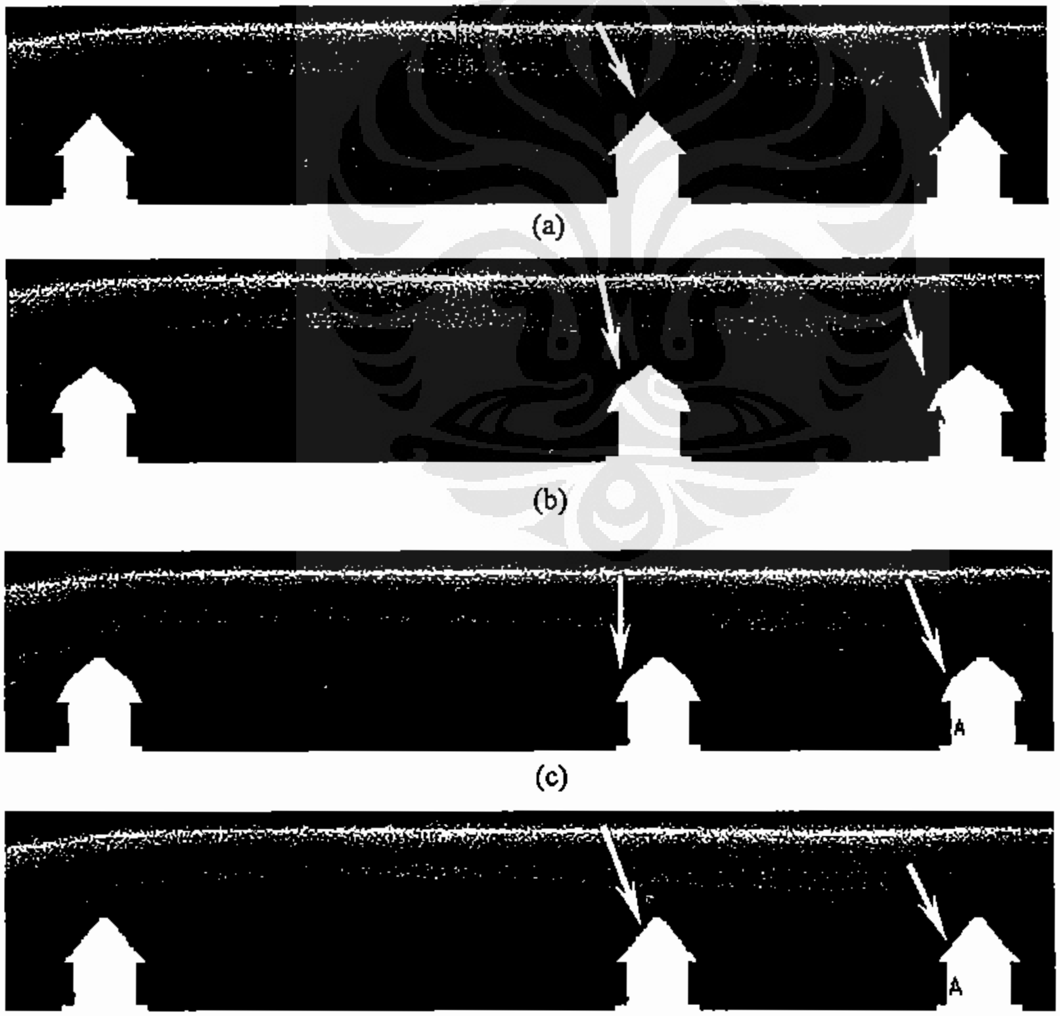
Figure 3. Typical meshes

4. Results and discussions

In traditional Balinese architecture, the building indicated as Model 1 is usually used as a kitchen or the parent's sleeping quarters. There are no open surfaces at roof level and only a small door. Therefore, there is no cross-ventilation. The buildings indicated as Models 2 and 4 are used as a granary. These buildings are fully open, therefore cross-ventilation occurs everywhere in the building, except at the roof. The building indicated as Model 3 is used for ceremonies or as an assembly hall.

This building is open at the front side but oriented to the centre [8]. In the numerical simulations, all buildings are considered to be fully close.

The results of numerical simulations are shown in Figure 4. From the streamline plots, it can be seen that the reattachment points are slightly different for each model. Buildings in models 1 and 4 have higher reattachment points than those in models 2 and 3 on the second building, but lower on the third building. Therefore, the wind motion is only affected by the type of roof at roof level. The position of the reattachment point at the second and third buildings is also affected by the roof angle (roof pitch), with a greater roof angle producing a shorter reattachment length.



(a)

(b)

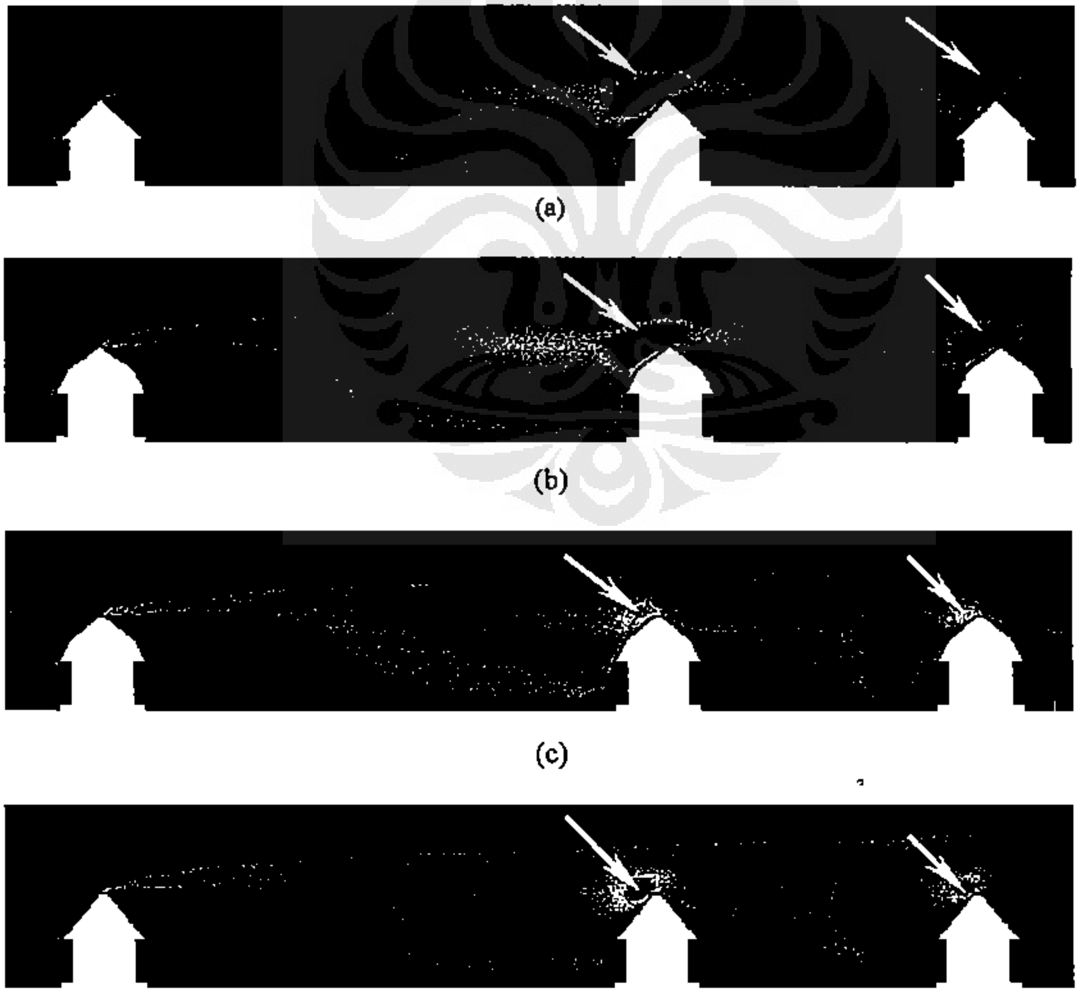
(c)

(d)

Figure 4. Streamline plots for a cluster of buildings with different roof types, arrows indicating the reattachment point

It can be seen from Figure 5 that both models 1 and 2 produce greater turbulent kinetic energy values than models 3 and 4, on the second and third buildings. This result also indicates that a roof which is flat at the top produces lower turbulent kinetic energy, and that a longer flat roof top reduces the turbulent kinetic energy. The highest turbulent kinetic energy occurs at the second building, followed by the third. The second building is used for ceremonies or as an assembly hall and the third building is the parent's sleeping quarters. This indicates that, in traditional Balinese architecture, there may be a relation between turbulent kinetic energy and building's function.

The second building, used for meetings, receives the highest turbulent kinetic energy. The use of nine pillars in this building will minimise the momentum effects and avoid the damage caused by the kinetic energy. The parent's sleeping quarters (the third building), which has eight posts, receives a lower turbulent kinetic energy than the second building. From this point of view, the use of pillars appears to indicate the need to protect the building to avoid possible damage, and correlates the traditional Balinese architecture to architectural aerodynamics.



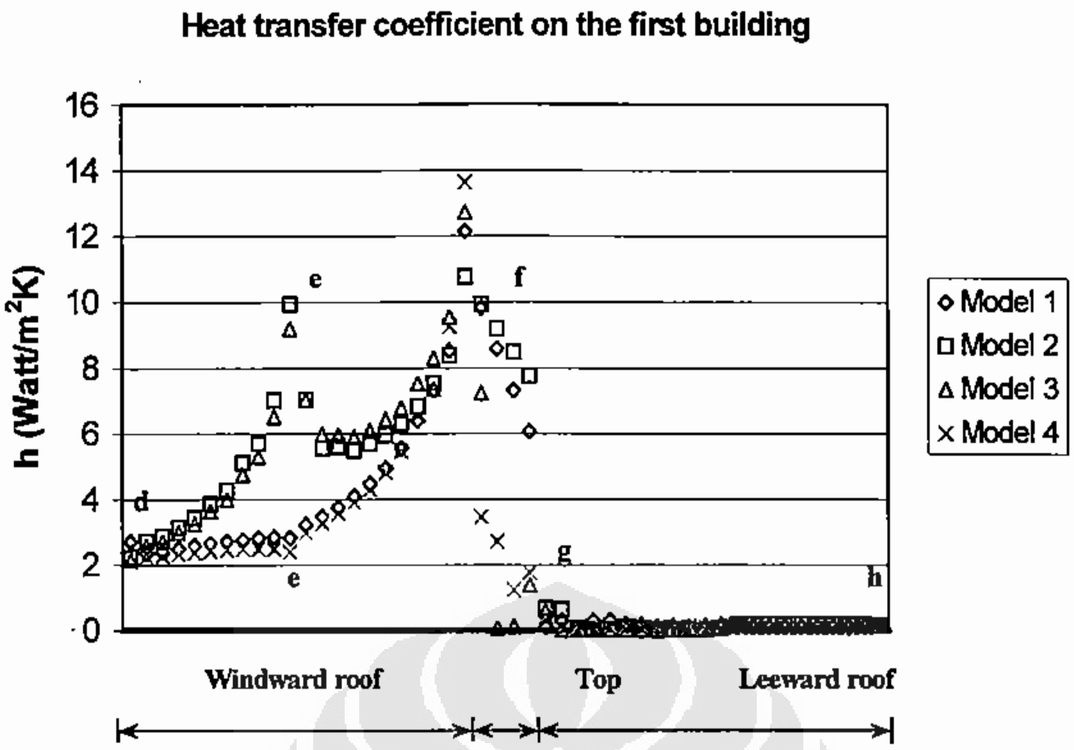
(a)

(b)

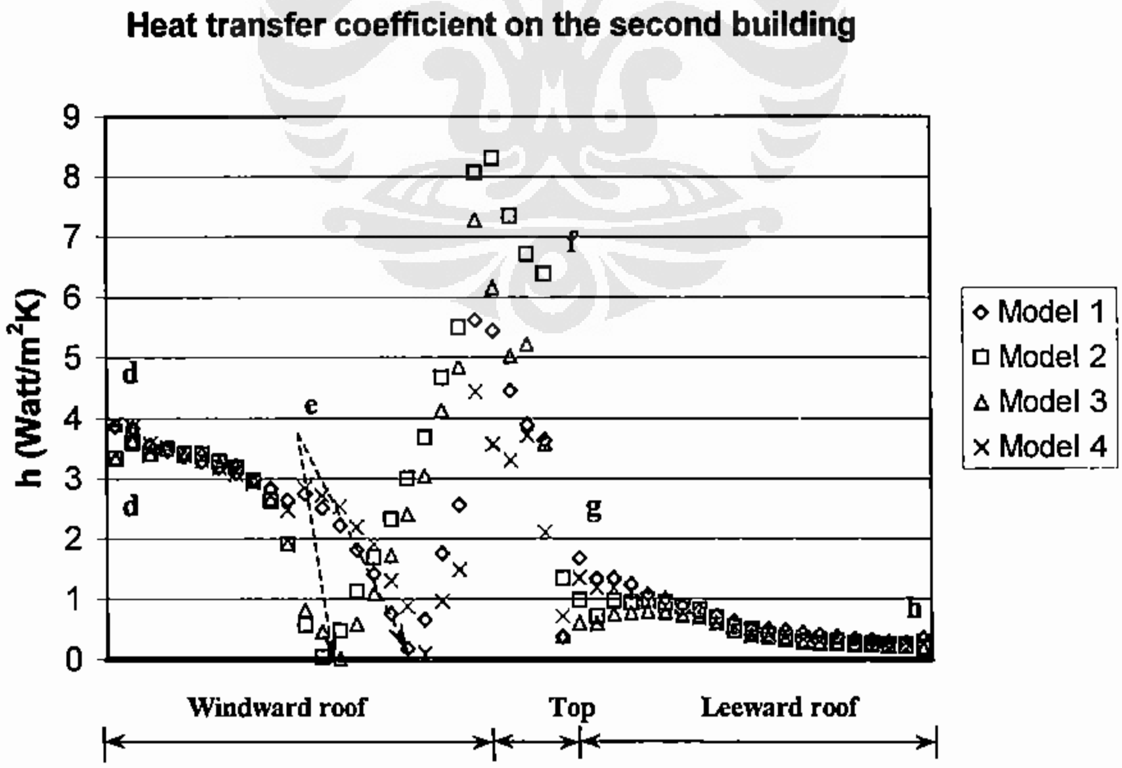
(c)

(d)

Figure 5 Turbulence kinetic energy plots for a cluster of buildings with different roof types, arrows indicating different results


Heat transfer coefficient on the first building
h (Watt/m2K)
16
14
12
10
8
6
4
2
0
d
e
e
f
g
h
Model 1
Model 2
Model 3
Model 4
Windward roof
Top
Leeward roof

(a)


Heat transfer coefficient on the second building
h (Watt/m2K)
9
8
7
6
5
4
3
2
1
0
d
d
e
f
g
h
Model 1
Model 2
Model 3
Model 4
Windward roof
Top
Leeward roof

(b)

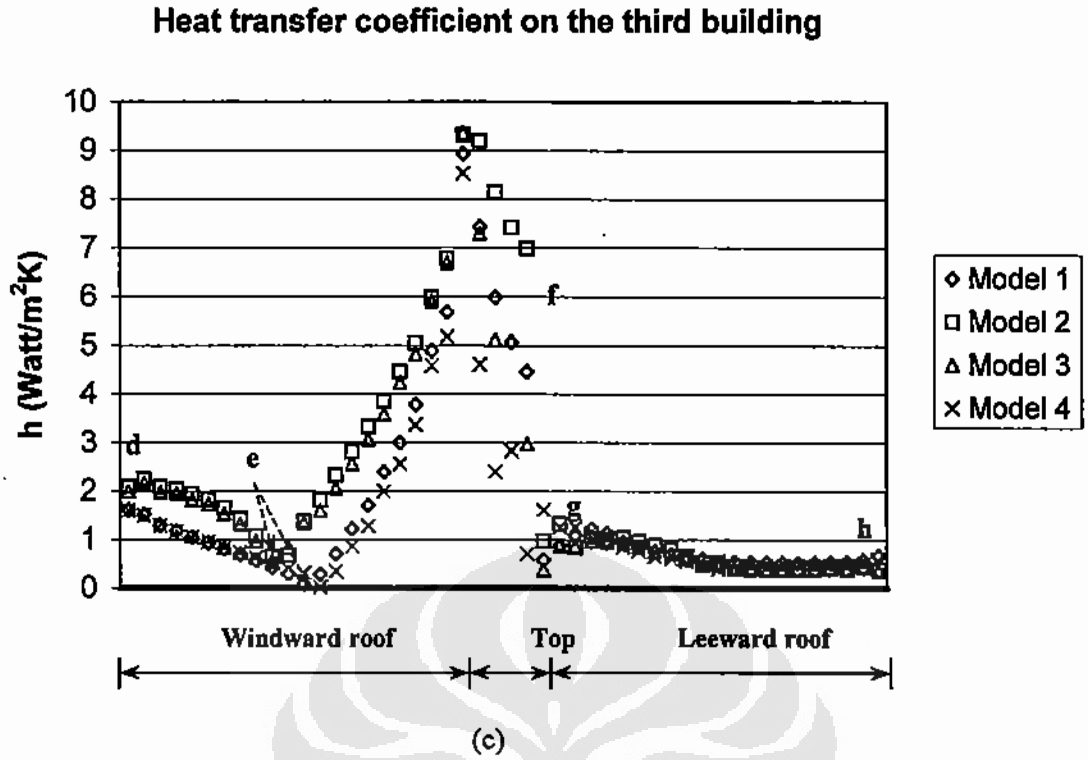


Figure 6. Heat transfer coefficient for different roof types

Heat transfer coefficients are presented in Figure 6. At the first building, it can be seen that both models 2 and 3 produce greater heat transfer coefficients, indicating that they are affected by roof angle, *i.e.* the greater the roof angle, the greater the heat transfer coefficient. At the second building, both models 2 and 3 have similar reattachment points (point *e*) which is lower than those of models 1 and 4. This result shows that the greater the roof angle, the shorter the reattachment point. Both models 2 and 3 produce a heat transfer coefficient slightly greater than models 1 and 4. Similar results occur at the third building where models 2 and 3 produce greater heat transfer coefficients than models 1 and 4.

It appears that buildings with greater roof angles produce greater heat transfer coefficients. This also indicates greater friction at building surfaces leading to increased lift force at the roof. Therefore, buildings as indicated by models 2 and 3 are subjected to greater lift force.

According to the above discussion, buildings in models 2 and 3 will increase the heat transfer to the surrounding. This is the reason why these models are used as granaries, since rice paddies and any other foods should be stored in a dry and cool place. This means that the first building is specially indicated to store food and is where the kitchen should be located.

5. Conclusions

Traditional houses in hot and humid climate zones are designed to utilise the wind for natural cooling. The type of roof affects the wind motion, especially at roof level. In a cluster of buildings, the reattachment point at the second and third buildings is affected by the roof angle (roof pitch).

A flat-top roof reduces turbulent kinetic energy. In this study, the highest turbulent kinetic energy occurs at the second building, followed by the third. The use of pillars in these buildings will minimise the momentum effects. There appears to be a relation between the buildings' name given in traditional Balinese architecture and the need to protect them against the damage caused by turbulent kinetic energy. Therefore, the building arrangement should be in the following order: four posts building at the front followed by six posts building, with the nine posts building in the middle and the eight posts building at the rear.

The temperature distribution at the first building is generally the lowest, with the second and third buildings having a relatively higher temperature. This can be directly related to thermal comfort of occupants, since the suggested temperature for residences, apartments, convalescent homes and homes for the aged (third building, the parent's sleeping quarters) is higher than that for conference rooms, meeting rooms or auditoriums (second building). The suggested temperature for kitchens and stores is the lowest (the first building). Therefore, there is a relation between the position of buildings and their function, with the thermal comfort of occupants. Storage rooms and kitchens should lie at the front side, ceremonial and meeting halls should lie in the middle and the parent's sleeping quarters should lie at the rear of the site.

It appears that traditional Balinese architecture has a relation with wind engineering, heat transfer and thermal comfort of occupants. The numerical investigations conducted here provide a contribution to a better understanding of traditional Balinese architecture and some design modifications to improve thermal comfort.

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