

Natural ventilation by stack effect in multi-span tropical greenhouse structures

(Pengalihudaraan semula jadi oleh kesan suhu di dalam struktur rumah hijau tropika berbilang rentang)

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Key words: natural ventilation, stack effect, multi-span, greenhouse structure

Abstract

Natural ventilation is defined as the number of volume air exchange per hour per unit floor area. It is necessary to reduce high indoor air temperature and humidity. In addition, it also maintains carbon dioxide concentration as outside of the greenhouse. Natural ventilation is preferred because ventilation opening is built in the greenhouse, cheaper construction cost, and no energy and maintenance are required as compared to the mechanical ventilation system. A mathematical model to quantify natural ventilation rates by stack effect was developed and verified under the multi-span of large-scale greenhouse structures. Four naturally ventilated tropical greenhouse structures had been designed and constructed at MARDI. The structures are single, double, triple and quadruple spans that have floor areas of 500 m², 1,000 m², 1,500 m² and 2,000 m² respectively. This paper presents the validation of model developed to quantify natural ventilation rates by stack effect inside the constructed structures, which is very crucial of high in-house temperature built up in the tropics. Moreover, the effects of height on ventilation rates were also discussed. The regression equations of stack effect ventilation rates against temperature differences between inside and outside structure were found to be $\Phi_s = 0.0221\Delta T^{0.4945}$, $\Phi_s = 0.0149\Delta T^{0.4933}$, $\Phi_s = 0.0117\Delta T^{0.4917}$ and $\Phi_s = 0.0098\Delta T^{0.4906}$ for single, double, triple and quadruple spans respectively. In addition, the coefficient of determinations shows strong relationship with $R^2 = 0.9999$, $R^2 = 0.9999$, $R^2 = 0.9998$ and $R^2 = 0.9998$ for single, double, triple and quadruple spans respectively. The comparison between calculated and measured in-house air temperatures has shown that they are significantly comparable to each other. The effects of three levels of height (3.4 m, 4.0 m and 5.0 m) between the top and bottom openings on ventilation rate were also studied. The results showed that the ventilation rate increased with increase in heights (distance between middle of side opening and middle of roof opening) of structures.

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Introduction

Greenhouse is defined as a special construction used to protect plants from undesired climate variation that provides conducive in-house environment for plant production (Bin Qadhi and Haidrah 1999). This technique is necessary to replace high risk of open field production against high rainfall, extreme solar radiation, weed competition, and disease and insect damages. The main function of greenhouse production system is to increase the yield and quality of vegetable, fruit, flower and herb production. Moreover, the crop production can be made continuously throughout the year. In Malaysia, crop production under greenhouses plays an important cultural system in supplying sufficient food to substitute the high import bill of processed and unprocessed horticultural products. Currently, the import bill on food worth more than RM13 billion annually (Rezuwan 2002).

The design of greenhouse in the tropics is significantly different compared to that in the cool climate region. Greenhouse in the tropics is of the heat dissipated type, while in the temperate region it is heat conservative. Therefore, ventilation is necessary to remove excess heat built up during the hot sunny day. Ventilation is the number of air exchange between inside and outside of the greenhouse through the openings per unit time and floor area. Ventilation systems, in general, are operated as natural ventilation and forced ventilation (Baptista et al. 1999). Usually, natural ventilation is induced by the stack or wind effects or a combination of both, while forced ventilation is driven by electrical fans or other mechanical means. Natural ventilation system is more preferred because of less energy and low maintenance as compared to the forced ventilation method (Rezuwan 1999).

Air exchange occurs when there is a pressure difference across the ventilator opening. Pressure difference is usually induced by the wind force acted at the

eave level (wind effect) or temperature difference between inside and outside of the greenhouse (stack or chimney effect). In general, both the wind and stack effects occur together. Ventilation is necessary to provide air exchange and good climate control in the greenhouse. It limits the temperature rise on hot days, controls excessive humidity caused by transpiration and prevents excessive depletion of the carbon dioxide concentration. Therefore, an understanding of air exchange rate is necessary because it directly affects the development and production of crops (Rezuwan 1999; Montero et al. 2000, 2001; Rezuwan 2002; Rezuwan et al. 2004).

The effect of floor area on natural ventilation in a large animal enclosed housing has been conducted by Albright (1978). He found that bigger floor area with smaller opening vents gave poor ventilation rate and higher in-house temperature. However, natural ventilation study on porous greenhouse is yet to be made. Porous greenhouse is where all the side walls permit air movement freely throughout the insect-screen. Stack effect is very crucial in the tropics when there is no wind. Therefore, this paper presents the development of stack effect natural ventilation model and verification on the multi-span of naturally ventilated tropical greenhouse structure. The effect of structure height on ventilation rate is also presented.

Materials and methods

Greenhouse structure

Naturally ventilated tropical greenhouse structures were designed and constructed at MARDI Serdang. The design considered engineering code of practices, and plant physiological and agronomics requirements. The single-span of the structure was 50 m long x 10 m wide x 4.5 m high which has straight side walls and tunnel roof shape with jack-roof. The double, triple and quadruple spans were also constructed in the prefabricated and modular form (*Plates 1 and 2*). All structures were made

of galvanized steel frame, transparent polyethylene film (180 μm thick) roofing and polyethylene insect-screen (800 μm mesh) side cladding. The dimension of the greenhouse structures is presented in *Table 1*.



Plate 1. Single-span greenhouse



Plate 2. Quadruple-span greenhouse

Data collection

The microclimate parameters were measured continuously for more than 6 months by using Integrated Data Acquisition and Monitoring System. In addition, hand-held electronic temperature sensors were also used to support the measurement and verification. The system consisted of computer software, circuit integration, data logger, electronic actuators and sensors. The sensors used were temperature, humidity, wind speed, wind direction, wind pressure, rain gauge, carbon dioxide and light intensity sensors. Measurement was taken at the middle inside the house and also the outside. All sensors were calibrated before taking the measurements to minimize error or unreliable data.

Model development

Ventilation by stack effect The temperature difference between the confined air in a building and the surrounding air will produce ventilation by natural convection through suitable openings (Foster and Down 1987). Ventilation rate as a function of ΔT (difference between inside and outside temperature), height between the middle of side and roof opening areas h , floor area A_g , side area A_s and roof area A_R , is as follows:

$$\Phi_s = (\Delta T, h, A_g, A_s, A_R) \quad (1)$$

Air will move in through the lower openings in one direction and out through the higher opening in the opposite direction. At some height h , the pressures inside and outside will be equal and there will be no air flow, where the neutral plane is defined to be at this height.

Table 1. Dimensions of naturally ventilated tropical greenhouse structures

Structure	Length (m)	Width (m)	Height (m)	Volume (m^3)	Floor area (m^2)	Cover area (m^2)
Single-span	50	10	4.5	2300	500	600
Double-span	50	20	4.5	4600	1000	1200
Triple-span	50	30	4.5	6900	1500	1600
Quadruple-span	50	40	4.5	9200	2000	2400

The height of the neutral (\bar{h}) is found by solving:

$$\sum_{j=1}^n \int_{A_j} \frac{|\bar{h} - h|^{\frac{3}{2}}}{\bar{h} - h} dA = 0 \quad (2)$$

Ventilation rate can be calculated by (Foster and Down 1987) as:

$$\Phi_s = C_d \left(\frac{2g\Delta T}{T_o} \right)^{\frac{1}{2}} \sum_{j=1}^n \int_{A_j(\bar{h})} \frac{|\bar{h} - h|^{\frac{3}{2}}}{\bar{h} - h} dA \quad (3)$$

Then, is deduced to

$$\Phi_s = C_d \left(\frac{2g\Delta T}{T_o} \right)^{\frac{1}{2}} \sum_{j=1}^n \int_{A_s}^{A_R} \frac{|\bar{h} - h|^{\frac{3}{2}}}{\bar{h} - h} dA \quad (4)$$

$$\bar{h} = \frac{h}{1 + \left(\frac{A_s}{A_R} \right)^2} \quad (5)$$

The ventilation rate is then established by integration of equation (4) over the area A_s

$$\Phi_s = C_d \left(\frac{2gh\Delta T}{T_o} \right)^{\frac{1}{2}} \left[\frac{1}{A_s^2} + \frac{1}{A_R^2} \right]^{-\frac{1}{2}} \quad (6)$$

According to Rezuwan (1999) the mass flow equation the total inflow Φ_{in} ($m^3 s^{-1}$) is equal to the total outflow Φ_{out} ($m^3 s^{-1}$). At this point, there were two openings at the bottom and two openings on top of neutral plane.

$$2 \Phi_{in} + 2 \Phi_{out} = 0 \quad (7)$$

Theoretically, the inlet air flow is equal to outlet air flow. This gives the general equation to quantify stack effect ventilation rate in single-span structure as:

$$\Phi_s = C_d \left(\frac{2gh\Delta T}{T_o} \right)^{\frac{1}{2}} \left[\frac{1}{A_s^2} + \frac{1}{A_R^2} \right]^{-\frac{1}{2}} \quad (8)$$

where Φ_s is the ventilation rate ($m^3 m^2 s^{-1}$), C_d is the discharge coefficient, A_g is the

floor area of the structure (m^2), g is the acceleration due to gravity ($m s^{-2}$), h is the height between two openings (m), ΔT is the air temperature difference between the inside and outside of the structure ($^{\circ}C$), T_o is the outside air temperature ($^{\circ}C$), A_s is the side opening area (m^2) and A_R is the roof opening area (m^2).

In the multi-span structure ventilation rate by stack effect can be calculated by:

$$\Phi_s = \frac{2C_d}{A_g} \left(\frac{2gh\Delta T}{T_o} \right)^{\frac{1}{2}} \left[\frac{1}{A_s^2} + \frac{1}{\sum_{i=1}^n A_R^2} \right] \quad (9)$$

where n is the number of spans.

Inside the house temperature calculation

Inside air temperature was calculated by developed ventilation rate model. Air temperature was also measured to verify the validity of the model. The comparison between measured and calculated was used to address the difficulty of using tracer gas method in porous large-scale greenhouse structures. Tracer gas method is a standard direct measurement of ventilation rate.

Inside temperature can be calculated by:

$$T_i = \Delta T + T_o \quad (10)$$

ΦT can be calculated by equation (11) for single and multi-span.

$$\Delta T = \left[\frac{A_g T_o^{\frac{1}{2}} \left(\frac{1}{A_s^2} + \frac{1}{\sum_{i=1}^n A_R^2} \right)^{\frac{1}{2}} \Phi_s}{2C_d (2gh)^{\frac{1}{2}}} \right] \quad (11)$$

where Φ_s is the ventilation rate ($m^3 m^2 s^{-1}$) by stack effect, n is the number spans and ΔT is the value inside temperature minus with the outside value ($^{\circ}C$).

Verification of the model

The collected air temperatures at no wind were substituted in equation 8 to quantify the calculated ventilation rate. This is to address the high heat built up inside the greenhouse during the no wind condition. The regression relationship between ventilation rate and temperature difference between inside and outside of the greenhouse was evaluated to verify the accuracy of the developed mathematical model. In addition, equation 9 was also verified to ensure there is no significant difference between calculated and measured inside the house temperature.

Results and discussion

Natural ventilation by stack effect

Ventilation rate by stack effect was calculated using equations (8) and (9) for single and multi-spans respectively. Based on previous study, the discharge coefficient of 800 μm mesh was taken as 0.411 (Rezuwan 1999). Figure 1 shows the relationship between ventilation rate and temperature difference in the single, double, triple and quadruple-span structures. The ventilation rate increased with the increase in the temperature

difference between the inside and outside of structure. The regression equations of the stack effect ventilation rates against temperature differences between inside and outside structure were found to be $\Phi_s = 0.0221\Delta T^{0.4945}$, $\Phi_s = 0.0149\Delta T^{0.4933}$, $\Phi_s = 0.0117\Delta T^{0.4917}$ and $\Phi_s = 0.0098\Delta T^{0.4906}$ for single, double, triple and quadruple-span respectively. All the regression equations follow the theory of power curve with exponent index of 0.5. These exponent indices are in a good agreement with index of 0.5 as established in equations (8), (9), Rezuwan (1999), Redzuwan et al. (2004) and Albright (1978). In addition, the coefficient of determinations showed strong relationships between ventilation rate and temperature difference which were found as $R^2 = 0.9999$, $R^2 = 0.9999$, $R^2 = 0.9998$ and $R^2 = 0.9998$ for single, double, triple and quadruple-span respectively.

Figure 1 also shows the effect of floor areas on natural ventilation rate for the single, double, triple and quadruple-span structures. The single-span structure ventilation rate was the highest as compared to the other structures. This is because of the lower temperature difference between inside and outside of the smaller structure as

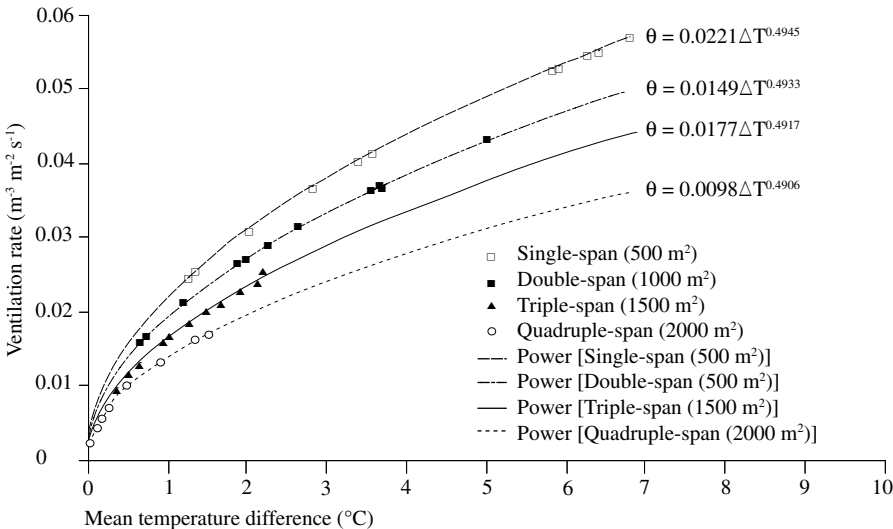


Figure 1. Stack effects and effects of floor areas on ventilation rates for single, double, triple and quadruple-span greenhouses

compared to the bigger floor area. According to equations (8) and (9), higher temperature difference will give higher ventilation rate.

The stack effect regression equations of the single, double, triple and quadruple-span structures are summarized in Table 2. All the exponent indices are in a good agreement with index of 0.5 in equations (8), (9) (Albright 1978; Rezuwan 1999, Rezuwan et al. 2004). In addition, the adjusted coefficients of determinations (R^2) have shown a strong relationship between ventilation rates and temperature differences with regard to the size of the floor areas. Most of the coefficients of determinations are 0.999. The bigger floor area has lower ventilation rate because of higher temperature difference between inside

and outside of the structure. That means the inside temperature is higher than the smaller greenhouse. Lower inside temperature was achieved by providing higher ratio of vent opening with floor area and facilitating convection air movement in the greenhouse. Therefore, the bigger floor area greenhouse gives higher inside air temperature that requires more vent opening area for crop production in a hot and humid tropical weather.

Inside temperature calculation

Inside temperature was calculated using equation (10), where the ΔT was calculated by using equations (11) for single and multi-span structure. Figure 2 shows the relationship between measured and

Table 2. Regression equations of ventilation rate by stack effects for natural ventilation in single, double, triple and quadruple-span greenhouses

Structure	Regression equation	Adjusted R^2	No. of observations
Single-span (500 m ²)	$\Phi_s = 0.0221\Delta T^{0.4945}$	0.9999	30
Double-span (1,000 m ²)	$\Phi_s = 0.0149\Delta T^{0.4933}$	0.9999	30
Triple-span (1,500 m ²)	$\Phi_s = 0.0177\Delta T^{0.4917}$	0.9998	30
Quadruple-span (2,000 m ²)	$\Phi_s = 0.0098\Delta T^{0.4906}$	0.9998	30

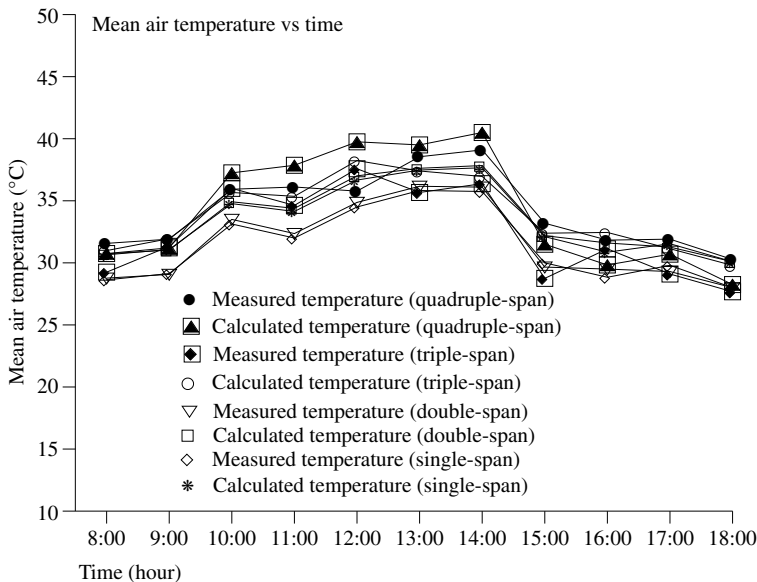


Figure 2. Relationship between measured and calculated temperatures inside single, double, triple and quadruple-span greenhouses

calculated temperatures inside single, double, triple and quadruple-span structures. The comparison between calculated and measured inside temperatures showed there is no significant difference between them. The Standards Errors of Means were found to be less than 1 °C which are between 0.3500, 0.1650, 0.8225 and 0.6100 for single, double, triple and quadruple-span structures respectively. The agreements between the calculated and measured temperatures have indicated the validity of the models and of its ability to yield the correct values to quantify ventilation rate.

Effect of height on ventilation

Three heights studied were 3.4 m, 4.0 m and 5 m. *Figure 3* shows the effects of height on ventilation rate in single, double, triple, and quadruple-span. Ventilation rate increased with the increase in the height between the openings (distance between middle of bottom side opening and middle of roof opening at the top) of structure. This

is because higher height has bigger space for air movement and causes fast air exchanges. The stack effect regression equations of single, double, triple and quadruple-span structures are summarized in *Table 3*. All the exponent indices are in a good agreement with index of 0.5 in equations (7), (8) (Albright 1978; Rezuwan 1999 and 2004). In addition, the adjusted coefficients of determinations (R^2) show strong relationship between ventilation rates and temperature differences with regard to the size of the floor areas. Most of the coefficients of determinations are 0.999.

Conclusion

The developed stack effect mathematical model helps in the design and quantification ventilation rate of the single, double, triple and quadruple-span of naturally ventilated tropical greenhouse in the tropics. Understanding of stack effect is very important because of high inside air temperature during the no wind condition.

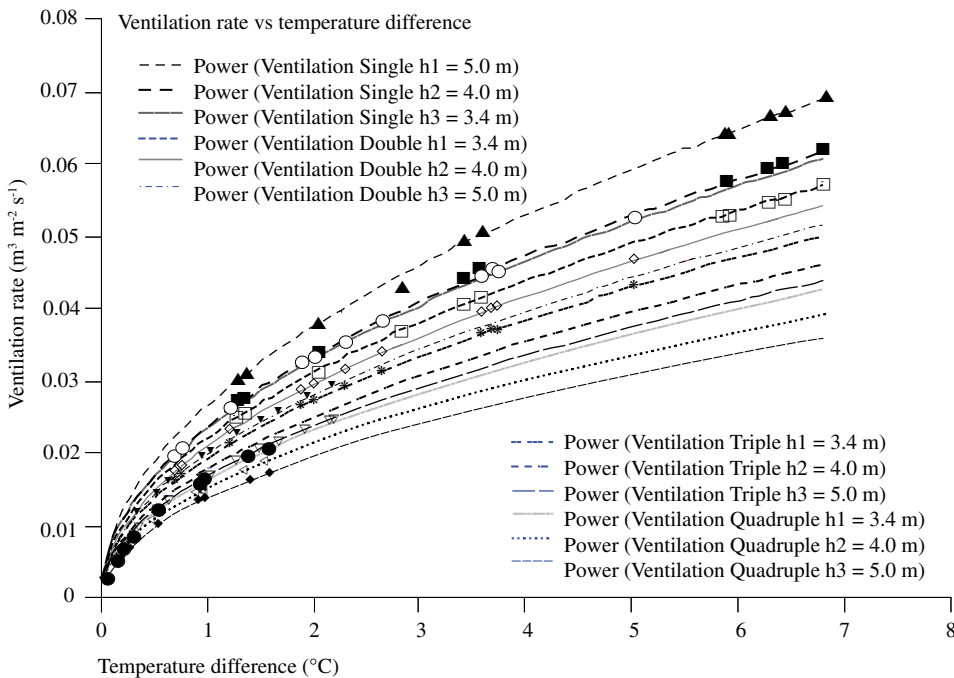


Figure 3. Effect of height on ventilation rate for single, double, triple and quadruple-span greenhouses

Table 3. Regression equations of ventilation rates by stack effects for natural ventilation in single, double, triple and quadruple-span greenhouses

Structure	Height (m)	Regression equation	Adjusted R ²	No. of observations
Single-span	h ₁ = 3.4	$\Phi_s = 0.0221\Delta t^{0.4945}$	0.9999	30
	h ₂ = 4.0	$\Phi_s = 0.024\Delta t^{0.4945}$	0.9999	30
	h ₃ = 5.0	$\Phi_s = 0.0268\Delta t^{0.4945}$	0.9999	30
Double-span	h ₁ = 3.4	$\Phi_s = 0.0149\Delta t^{0.4933}$	0.9999	30
	h ₂ = 4.0	$\Phi_s = 0.0162\Delta t^{0.4932}$	0.9999	30
	h ₃ = 5.0	$\Phi_s = 0.0181\Delta t^{0.4932}$	0.9999	30
Triple-span	h ₁ = 3.4	$\Phi_s = 0.0117\Delta t^{0.4917}$	0.9998	30
	h ₂ = 4.0	$\Phi_s = 0.0127\Delta t^{0.4917}$	0.9998	30
	h ₃ = 5.0	$\Phi_s = 0.0142\Delta t^{0.4925}$	0.9999	30
Quadruple-span	h ₁ = 3.4	$\Phi_s = 0.0098\Delta t^{0.4906}$	0.9998	30
	h ₂ = 4.0	$\Phi_s = 0.0106\Delta t^{0.4906}$	0.9998	30
	h ₃ = 5.0	$\Phi_s = 0.0118\Delta t^{0.4917}$	0.9999	30

h₁, h₂, h₃ = Distance between the middle bottom opening and middle top opening (m)

High inside temperature causes heat stress to crop growth that is detrimental to the plants. Ventilation rate by stack effect will increase with increasing temperature difference between inside and outside structure.

Ventilation rate inside multi-span structure (bigger floor area) was found to be lower as compared to the single-span structures. This is due to the higher air temperature difference inside this type of greenhouse. In addition, the bigger floor area gave higher inside temperature because bigger floor area gives more space for air travelling to the outside and less roof ventilators opening to induce air exchanges. The comparison between calculated and measured inside temperature showed there is no significant difference between them. The effect of height on ventilation rate is also crucial in the greenhouse design. The ventilation rate is increased with the increase in the height (distance between middle of side opening and middle of roof opening) of structure.

Acknowledgement

The authors would like to thank those who are directly or indirectly involved in this research.

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Abstrak

Pengalihudaraan semula jadi ditakrifkan sebagai jumlah isi padu udara bertukar dalam sejam seunit luas lantai struktur rumah hijau. Ia sangat diperlukan untuk menurunkan suhu dan kelembapan udara dalaman yang terlalu tinggi. Selanjutnya dapat mengekalkan kandungan karbon dioksida seperti di persekitaran luaran. Pengalihudaraan semula jadi dipilih kerana bukaan pengalihudaraannya terbina pada struktur, pembinaannya murah, dan tiada tenaga serta penyelenggaraan diperlukan berbanding dengan sistem pengalihudaraan secara mekanikal. Satu model matematik telah dibangunkan dan disahkan untuk mengira kadar pengalihudaraan semula jadi disebabkan kesan perbezaan suhu di dalam dan di luar struktur rumah hijau pelbagai rentang berskala besar. Empat struktur rumah hijau berpengalihudaraan semula jadi telah direka bentuk dan dibina di MARDI. Struktur tersebut ialah rentang tunggal, rentang kembar, rentang kembar tiga dan rentang kembar empat masing-masing berkeluasan lantai 500 m², 1,000 m², 1,500 m² dan 2,000 m². Kertas ini membentangkan pengesahan model matematik yang dibangunkan terhadap pengiraan kadar pengalihudaraan semula jadi disebabkan kesan suhu di dalam struktur yang telah dibangunkan. Di samping itu, kesan ketinggian struktur terhadap kadar pengalihudaraan semula jadi juga dibincangkan. Persamaan regresi bagi kadar pengalihudaraan semula jadi disebabkan kesan perbezaan suhu dalaman dan luaran struktur didapati masing-masing $\Phi_s = 0.0221\Delta T^{0.4945}$, $\Phi_s = 0.0149 \Delta T^{0.4933}$, $\Phi_s = 0.0117 \Delta T^{0.4917}$ dan $\Phi_s = 0.0098 \Delta T^{0.4906}$ untuk rentang tunggal, rentang kembar, rentang kembar tiga dan rentang kembar empat. Tambahan dari itu, pekali regresi menunjukkan perhubungan yang tinggi iaitu masing-masing $R^2 = 0.9999$, $R^2 = 0.9999$, $R^2 = 0.9998$ and $R^2 = 0.9998$ untuk rentang tunggal, rentang kembar, rentang kembar tiga dan rentang kembar empat. Perbandingan antara suhu pengiraan dengan pengukuran mendapati nilainya hampir sama. Kesan tiga aras ketinggian (3.4 m, 4.0 m and 5.0 m) antara titik tengah bukaan pengalihudaraan atas dengan bukaan pengalihudaraan bawah juga dikaji. Didapati kadar pengalihudaraan akan bertambah mengikut pertambahan ketinggian antara bukaan tersebut.