

Napassawan Khammayom; Maruyama, Naoki; Chatchawan Chaichana

Article

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Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Napassawan Khammayom; Maruyama, Naoki; Chatchawan Chaichana (2020) : Simplified model of cooling/heating load prediction for various air-conditioned room types, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 344-351, <https://doi.org/10.1016/j.egyr.2019.11.086>

This Version is available at:

<https://hdl.handle.net/10419/243900>

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The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019),
20–23 September 2019, Okinawa, Japan

Simplified model of cooling/heating load prediction for various air-conditioned room types

Napassawan Khammayom^a, Naoki Maruyama^b, Chatchawan Chaichana^{c,*}

^a Master's Degree Program in Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, 50200, Thailand

^b Division of Mechanical Engineering, Graduate School of Engineering, Mie University, Tsu, 514-8507, Japan

^c Department of Mechanical Engineering, Faculty of Engineering, Chiang Mai University, Chiang Mai, 50200, Thailand

Received 4 October 2019; accepted 22 November 2019

Abstract

The purpose of this study is to develop simplified cooling/heating load models for a various air-conditioned room, applying the Buckingham-Pi theorem. The model is used to estimate cooling/heating loads of air-conditioned room at reduced calculation time. An experimental room for cooling load had been set up at Chiang Mai University, Thailand in summer season during March to April in 2018. On the other hand, an experiment room for heating load had been set up at Mie University, Japan during December 2018 to February 2019. Room temperatures were set at 27 °C–25 °C for cooling and 24 °C–21 °C for heating. Collected data, such as room air temperature, room relative humidity, ambient temperature and solar radiation were used to calculate appropriate constants for cooling/heating load model. To validate the accuracy of the simplified model, calculated heating/cooling load from the model was compared to the calculated cooling/heating load from the traditional method. The results demonstrated that the simplified model developed from Buckingham-Pi theorem could estimate the cooling/heating load by low computational complexity with acceptable accuracy, comparing to results from traditional calculation method.

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Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Simplified model; Cooling/heating load; Buckingham Pi; Dimensionless

1. Introduction

The rapid growing of population and economy in the last decade resulted in tremendous energy consumption and this growing trend will continue in the future. Electrical energy consumption is one of energy use in the building sector as well as the residential sector [1]. Due to climate changes, air conditioning (AC) is used for thermal comfort and improvement of indoor air quality. However, AC energy consumption is the greatest energy use more than half of total energy consumption in buildings in tropical region [2]. In addition, predictions show that the energy consumption in developed countries will be increasing by 50% during the next 15 years [1]. It

* Corresponding author.

E-mail address: c.chaichana@eng.cmu.ac.th (C. Chaichana).

<https://doi.org/10.1016/j.egy.2019.11.086>

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Nomenclature

\dot{Q}	Cooling/heating load (kW)
U	Overall heat transfer coefficient (W/m ² K)
A	Area (m ²)
T	Temperature (K)
G	Solar irradiation (W/m ²)

Greek symbols

α	Solar absorptivity of external surface
ε	Solar emissivity of external surface
τ	Solar transmissivity of external surface
σ	Stefan–Boltzmann constant is 5.67×10^{-8} W/m ² K ⁴

Subscripts

n	North side
s	South side
w	West side
c	Ceiling
f	Floor
win	Window
amb	Ambient
act	Actual
rad	Radiation
ΔT	Temperature difference

is known that a major electricity energy consumption of air conditioner is caused by heat transmission through building envelopes. To manage energy consumption, cooling/heating loads should be measured. Cooling/heating load measurement is not high cost but it is sometimes difficult to operate and there are several previous studies have focused on estimating energy use of Heating, Ventilation, and Air-Conditioning (HVAC) systems. In 2017 ASHRAE Fundamentals Handbook [3], the methods for estimating energy use are divided into two categories: Forward modeling and Inverse modeling.

Forward models as known as law-driven models, these begin with a physical description of the building such as location, geographical, wall materials, equipment, type of HVAC system, etc. Forward models are generally used method in building load prediction. Moreover, input variables are needed but these variables for this model are complexity [4]. It takes times to calibrate models, however the precision of this model still cannot be guaranteed. Inverse models or data-driven models. Output and input variables are known and measured. The purpose of this model is to resolve a mathematical description of the system and to forecast system parameters. The model approach often allows diagnosis of a system model that are easy to use and more precise predictors than forward models. Inverse models can generally be divided into black-box and gray-box models. Black box models consist of regression models, Artificial neural network (ANN), Support vector machine (SVM) and others. Moon et al. [5] developed an ANN model to set the required time for increasing indoor air temperature to setback temperature. Mba et al. [6] applied ANN for an hourly prediction of indoor air temperature and relative humidity in Douala, Cameroon. All data were collected for 2 years and used to determine the optimal ANN. Papantoniou and Kolokotsa [7] evaluated of ANN for outdoor air temperature prediction using data from four European cities. Protić et al. [8] developed a predictive model for heat load consumption using the SVM along with a discrete wavelet transform. The accuracy of black-box models is presented as RMSE (Root Mean Square Error), coefficient of determination (R^2) as well as The Pearson coefficient (r). In this approach, it requires various parameters but loses some basic engineering formulation. So black box models trend to have poor accuracy on account of lack of high-quality training data. On

the other hand, gray box models use important parameters and physical configuration of a building of HVAC system. There are many methods, for example thermal network models (RC model), Fourier series models and so on. Xu and Wang [9] developed a new simplified building model of an existing building using conduction transfer function (CTF) model through building envelopes and internal mass using the physical structure of a 2R2C thermal network model. They also presented a methodology for parameter optimization of 3R2C thermal network model for building envelopes based on frequency domain regression using genetic algorithm (GA). Ji et al. [4] proposed three RC-S model improvement for an hourly cooling load prediction. Braun and Chaturvedi [10] presented an inverse Gray box model for transient cooling load prediction. The error of the simplified model is about 2% compared with actual cooling loads. Moreover, the model also extrapolated well to locations and strategies not use in training process. The thermal network models are more accurate, requires less training, and are more robust. In previous studies, there are several methods of cooling or heating loads prediction. But in this paper, a dimensionless model is introduced to predict cooling load or heating load. The dimensionless number can be derived by using the Buckingham Pi theorem. The method reduces complex physical problems to be simplest and it has great generality and mathematical simplicity. This paper is classified as follows. Section 2 presents the methodology i.e. the model description and experimental set up. Section 3 explains the results and discussion. Finally, the conclusions are presented in Section 4.

2. Methodology

The objectives of the study are to simplify cooling/heating load model prediction for various air-conditioned room types and to estimate the cooling/heating load of air-conditioned room using Buckingham-Pi theorem. To obtain these objectives, the study contains three parts. First of all, cooling/heating load based on heat transfer theorem must be calculated for use as a reference. Materials of building envelopes are surveyed. Building material properties are collected and used as input for the calculation. Secondly, experiments are conducted to collect data such as air dry-bulb temperature, relative humidity, and solar radiation. The collected data are used in conjunction with the Buckingham-Pi theorem to formulate simplified cooling/heating load model. Thirdly, to verify the accuracy of the simplified model, outputs are compared to cooling/heating load from actual calculation ($\dot{Q}_{load,act}$). The error must be in appropriate value to use the simplified model estimating cooling/heating load of other air-conditioned rooms.

2.1. Experimental set up and cooling/heating load calculation using heat transfer theorem

To calculate cooling/heating load model using heat transfer theorem, measured data such as weather data, properties of material layers are required. Fig. 1 shows heat loss and heat gain through the experimental room's envelopes for heating. Building envelopes are the internal wall, ceiling, floor as well as an external wall. The external wall is considered as transmission and solar radiation loads. The rate of heat transfer of internal walls, external walls, ceiling, and floor can be expressed as Eq. (1), and the calculated net rate of radiation heat transfer between external walls/glass windows and surrounding is given by Eq. (2)

$$\dot{Q}_{\Delta T} = UA\Delta T \quad (1)$$

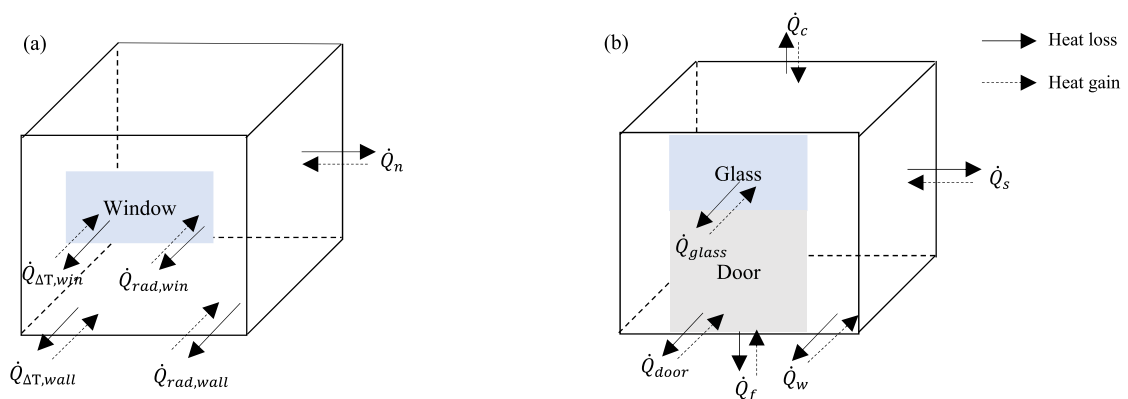


Fig. 1. Heat loss and heat gain through building envelopes (a) east side wall (b) west side wall.

$$\dot{Q}_{rad} = A(\alpha G) + A\varepsilon\sigma(T_{sky}^4 - T_{surface}^4) \tag{2}$$

where U is the overall heat transfer coefficient, A is the heat transfer surface area, ΔT is the temperature change between outside and inside room, α is the absorptivity, G is solar irradiation, ε is the emissivity, σ is Stefan–Boltzmann constant, T_{sky} is the effective sky temperature in K and $T_{surface}$ is the temperature of the surface in K.

2.1.1. Building description

In winter season (December 2018–February 2019), an experimental room located in Mie University is used for model validation with 17.31 m² (4.92 × 3.53 m.) and heights is 2.46 m. The window to wall ratio of east wall is approximately 55%. The office room is air-conditioned (heating mode) by one split type air conditioner. South-side room is not air-conditioned. In summer season (March 2018–April 2018), meeting room located in Chiang Mai University, Thailand on 8th floor is used for model testing. The floor area is approximately 65.9 m² and height is 3.5 m. The ratio of wall to window of west side is about 83%. The meeting room is air-conditioned (cooling mode) by two split type air conditioners. Artificial internal heat generation is used in this room (1600 W incandescent light bulb).

2.1.2. Experiment set up

To simplify the cooling/heating load model applying Buckingham-Pi theorem, indoor air dry-bulb temperature and relative humidity, outdoor air dry-bulb temperature and relative humidity, as well as solar radiation are needed. Experimental room temperature is set at 24 °C, 23 °C, 22 °C, and 21 °C for heating mode. Both indoor and outdoor air dry-bulb temperatures are recorded by taking average values from thermocouple sensors. Solar radiation of east external wall and window are real-measured using Pyranometer that attached to the window. The actual measured cooling/heating load is calculated using return and supply air temperatures of the air conditioner. The measurement device installation for heating mode is shown in Fig. 2 and the measurement device installation for cooling mode is shown in Fig. 3. Experimental data from the tests are divided into 2 sets. The first set of data (only from heating mode experiment) is used for model validation. The second data set is used for verification of the obtained model.

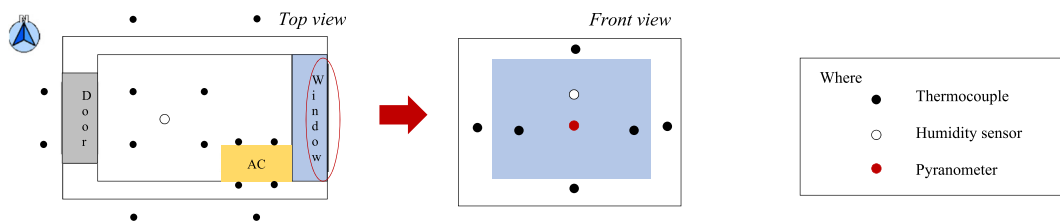


Fig. 2. Measurement device installation for heating mode.

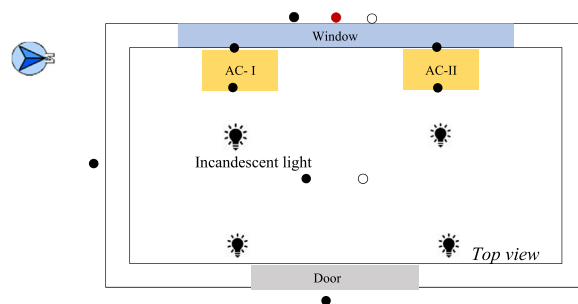


Fig. 3. Measurement device installation for cooling mode (Top view).

2.2. Development of simplified cooling/heating load using Buckingham Pi theorem and validation

In this study, dimensionless groups are generated to estimate cooling/heating load in an air-conditioned room. All factors of cooling/heating load such as the overall coefficient of heat transfer, area, air dry-bulb temperature along with solar radiation, are used to develop the dimensionless groups. Details of the dimensionless groups can be presented below.

$$\dot{Q}_{load} = f(U_c, U_f, U_{n,s}, U_{window}, U_w, U_{wall}, U_{glass}, U_{door}, A_{c,f}, A_{n,s}, A_{window}, A_{wall}, A_w, A_{glass}, A_{door}, T_{wall}, T_{window}, T_c, T_f, T_n, T_s, T_{amb}, T_w, T_{room}, G, \alpha_{wall}, \tau_{window}, \varepsilon_{window}, \varepsilon_{wall}, \sigma) \quad (3)$$

Dimensionless groups can be expressed as follows: Eqs. (4)–(31)

$$\pi_1 = \dot{Q}_{load} / U_f A_{c,f} T_{amb} \quad (4)$$

$$\pi_2 = G / U_f T_{amb} \quad (5)$$

$$\pi_3 = \sigma T_{amb}^3 / U_f \quad (6)$$

$$\pi_4 = U_c / U_f \quad (7)$$

$$\pi_5 = A_{n,s} / A_{c,f} \quad (8)$$

$$\pi_6 = U_{n,s} / U_f \quad (9)$$

$$\pi_7 = U_{window} / U_f \quad (10)$$

$$\pi_8 = U_w / U_f \quad (11)$$

$$\pi_9 = U_{wall} / U_f \quad (12)$$

$$\pi_{10} = U_{glass} / U_f \quad (13)$$

$$\pi_{11} = U_{door} / U_f \quad (14)$$

$$\pi_{12} = A_{window} / A_{c,f} \quad (15)$$

$$\pi_{13} = A_{wall} / A_{c,f} \quad (16)$$

$$\pi_{14} = A_w / A_{c,f} \quad (17)$$

$$\pi_{15} = A_{glass} / A_{c,f} \quad (18)$$

$$\pi_{16} = A_{door} / A_{c,f} \quad (19)$$

$$\pi_{17} = T_{window} / T_{amb} \quad (20)$$

$$\pi_{18} = T_c / T_{amb} \quad (21)$$

$$\pi_{19} = T_f / T_{amb} \quad (22)$$

$$\pi_{20} = T_n / T_{amb} \quad (23)$$

$$\pi_{21} = T_s / T_{amb} \quad (24)$$

$$\pi_{22} = T_w / T_{amb} \quad (25)$$

$$\pi_{23} = T_{room} / T_{amb} \quad (26)$$

$$\pi_{24} = T_{wall} / T_{amb} \quad (27)$$

$$\pi_{25} = \alpha_{wall} \quad (28)$$

$$\pi_{26} = \varepsilon_{wall} \quad (29)$$

$$\pi_{27} = \varepsilon_{window} \quad (30)$$

$$\pi_{28} = \tau_{window} \quad (31)$$

The dimensionless groups are selected based on their relations with each other. The target is to calculate the cooling/heating load. Therefore, the ratio of $\dot{Q}_{load} / U_f A_{c,f} T_{amb}$ is selected, Eqs. (7)–(19) and Eqs. (28)–(31) are constant. So, there are not a function with π_1 [11]. Below equation illustrates relationship of one dimensionless

group to the other groups.

$$\frac{\dot{Q}_{load}}{U_f A_{c,f} T_{amb}} = f\left(\frac{G}{U_f T_{amb}}, \frac{\sigma T_{amb}^3}{U_f}, \frac{T_{window}}{T_{amb}}, \frac{T_c}{T_{amb}}, \frac{T_f}{T_{amb}}, \frac{T_n}{T_{amb}}, \frac{T_s}{T_{amb}}, \frac{T_w}{T_{amb}}, \frac{T_{room}}{T_{amb}}, \frac{T_{wall}}{T_{amb}}\right) \quad (32)$$

In the above equation, it is essential to find the correlation of these dimensionless groups. Curve fitting is used. Experimental data is applied to Eq. (32). Then, least-squares regression is applied. The sum of squared residue is minimized by the best fit in the least squares. A residual is defined by difference between a real value and fitted value which is obtained from a model [12]. To validation the effectiveness and accuracy of the simplified model developed by Buckingham-Pi theorem, the outputs calculated heating load by simplified model are compared with that of the calculated heating load from traditional method (as a reference). Table 1. Shows the validation results of each model.

Table 1. Results of validation model.

Heat load model equation	Validating model RMSE (%)
$\dot{Q}_{load,modelPi2} = A_{c,f}(0.3050G + 0.0471U_f T_{amb})$	24.239
$\dot{Q}_{load,modelPi3} = A_{c,f} T_{amb}(1.4243\sigma T_{amb}^3 - 0.2701U_f)$	0.010
$\dot{Q}_{load,modelPi17} = U_f A_{c,f}(1.3805T_{window} - 1.3543T_{amb})$	0.015
$\dot{Q}_{load,modelPi18} = U_f A_{c,f}(-1.0539T_c + 1.1583T_{amb})$	27.727
$\dot{Q}_{load,modelPi19} = U_f A_{c,f}(-1.2706T_f + 1.3775T_{amb})$	0.091
$\dot{Q}_{load,modelPi20} = U_f A_{c,f}(-0.8777T_n + 0.9731T_{amb})$	0.035
$\dot{Q}_{load,modelPi21} = U_f A_{c,f}(-1.2350T_s + 1.3414T_{amb})$	0.049
$\dot{Q}_{load,modelPi22} = U_f A_{c,f}(-1.5984T_w + 1.7159T_{amb})$	0.058
$\dot{Q}_{load,modelPi23} = U_f A_{c,f}(-0.3099T_{room} + 0.3867T_{amb})$	0.117
$\dot{Q}_{load,modelPi24} = U_f A_{c,f}(2.0215T_{wall} - 1.9861T_{amb})$	0.129

2.3. Model verification

The simplified model was verified using three week’s heating operation in Mie and five day’s cooling operation in Chiang Mai. The root mean square error (RMSE) as Eq. (33) is used to calculate the prediction performance of different models.

$$RMSE = \sqrt{\frac{\sum_{k=1}^N (\dot{Q}_{act,k} - \dot{Q}_{model,k})^2}{N}} \quad (33)$$

where \dot{Q}_{act} is rate of heat loss/heat gain by forward model (also known as traditional method) at k th data point. \dot{Q}_{model} is rate of heat loss/heat gain calculated by the simplified model at k th data point. N is total number of data points.

3. Test results and discussion

The simplified model was further verified using other three week’s heating operation data in Mie, Japan and five days’ cooling operation data in Chiang Mai, Thailand. Both heating load and cooling load throughout the day were used to calculate root mean square error. RMSE is calculated for all models and the heat load model equations are shown in Table 2. U_f , $A_{c,f}$ and T_{amb} are defined as a repeating variable group that will be shown in every heat load equation models but remaining variables will be used in heat load equation which they appear. The root mean square error using *modelPi2*, *modelPi23* and *modelPi24* in heating case are 5.87%, 10.43% and 5.48% respectively compared with the calculated heating load that room temperature set up at 21 °C. While the root mean square error using *modelPi2*, *modelPi20* and *modelPi23* in cooling case are 7.27%, 5.37% and 2.48% respectively compared with the calculated cooling load which room temperature set up at 25 °C. The calculated hourly heating load profiles are presented in Fig. 4. The actual measured heating load is used for reference. It is clear that three simplified models provide acceptable accuracy and *modelPi2* can follow the profile of actual measured heating load well during solar radiation is present. The comparison between the model calculated and

Table 2. Test results.

Heat load model equation	RMSE (%)	
	Heating case	Cooling case
$\dot{Q}_{load,model Pi2} = A_{c,f}(0.3050G + 0.0471U_f T_{amb})$	5.87	7.27
$\dot{Q}_{load,model Pi3} = A_{c,f} T_{amb}(1.4243\sigma T_{amb}^3 - 0.2701U_f)$	14.23	58.22
$\dot{Q}_{load,model Pi17} = U_f A_{c,f}(1.3805T_{window} - 1.3543T_{amb})$	16.41	48.85
$\dot{Q}_{load,model Pi18} = U_f A_{c,f}(-1.0539T_c + 1.1583T_{amb})$	13.17	12.38
$\dot{Q}_{load,model Pi19} = U_f A_{c,f}(-1.2706T_f + 1.3775T_{amb})$	13.79	11.49
$\dot{Q}_{load,model Pi20} = U_f A_{c,f}(-0.8777T_n + 0.9731T_{amb})$	11.12	5.37
$\dot{Q}_{load,model Pi21} = U_f A_{c,f}(-1.2350T_s + 1.3414T_{amb})$	11.27	10.39
$\dot{Q}_{load,model Pi22} = U_f A_{c,f}(-1.5984T_w + 1.7159T_{amb})$	11.94	15.95
$\dot{Q}_{load,model Pi23} = U_f A_{c,f}(-0.3099T_{room} + 0.3867T_{amb})$	10.43	2.48
$\dot{Q}_{load,model Pi24} = U_f A_{c,f}(2.0215T_{wall} - 1.9861T_{amb})$	5.48	40.21

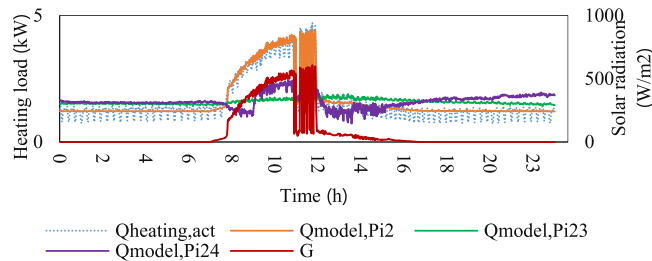


Fig. 4. Solar radiation profile along with calculated hourly heating load (validation-winter case).

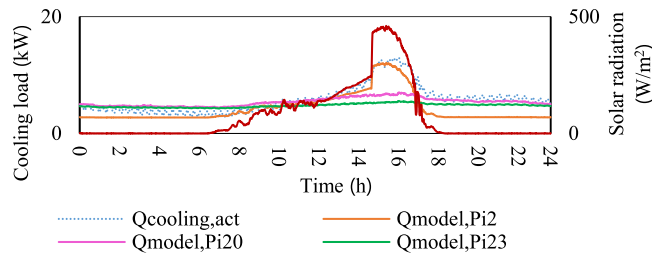


Fig. 5. Solar radiation profile along with calculated hourly cooling load (validation-summer case).

actual measured hourly cooling load is shown in Fig. 5. The hourly cooling load is calculated by *modelPi2*, *modelPi20* and *modelPi23* are compared to the actual measured cooling load. It can be seen that *modelPi2* is more accurate followed trends of cooling load than *modelPi20* and *modelPi23*.

In addition, the heat load between daytime and night-time is quite different. During there is no solar radiation, heat load in air-conditioned room is rather stable. The results show that the maximum actual measured cooling load is 15.45 kW of solar radiation hours of 13:00–16:00 while an averaged actual measured cooling load is 5 kW. Moreover, the maximum actual measured heating load is 5.3 kW when solar radiation is present of 9:00–11:00 and an average is 1.3 kW. It is obvious that the solar radiation has great effect on heating and cooling loads. During the daytime, where solar radiation is present, the models cannot predict heat load well. The error of heat load prediction during this time can be as high as 100%. However, *modelPi2* is the best calculated cooling and heating load during there is solar radiation with 7.27% and 5.87% RMSE. However, in terms of cooling/heat load, *modelPi23* is the best suitable for estimating building cooling and heating load because of low RMSE.

4. Conclusion

In this research, the simplified model applying Buckingham-Pi theorem is developed. The model is used to calculate heating/cooling load. The simplified model was verified under several conditions. Test results show that *modelPi24* is the best model calculated heating load with RMSE 5.48% compared to actual measured heating load. *modelPi23* is the best with RMSE 2.48% compared to actual measured cooling load. The simplified *modelPi23* applying Buckingham-Pi theorem is generally accurate for calculating the cooling/heating load without knowledge of building construction. Area's scope between 17.3 m² to 65 m² and room's temperature range between 21 °C to 27 °C. It can be said that *modelPi23* is the best model for calculating building heating/cooling load in reality, however *modelPi23* is sensitive to the profile of solar radiation so *modelPi2* is an alternative model that accurately calculated heating/cooling load while solar radiation is present.

Acknowledgments

This research is financially supported by Energy Technology for Environment (ETE) Research Center, Thailand, the Graduate School, and Faculty of Engineering, Chiang Mai University, Thailand under Research Support Program. The authors also wish to thank Department of Mechanical Engineering, Mie University, JAPAN for providing support during experiment. Financial support from the Energy Research and Development Institute Nakornping, Chiang Mai University, Thailand is also acknowledged.

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