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A Novel Approach for the Assessment of Thermal Insulation in Buildings Using Infrared Thermography and Artificial Intelligence

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Abstract

Buildings consume high energy for space and water heating, and thereby contribute largely to greenhouse gas emission. Improving thermal insulation of buildings' envelop can significantly reduce energy consumption for space heating as well as decrease greenhouse gas emission. However, prior to the retrofitting of a building it is required to evaluate the current level of wall insulation to estimate the additional requirements. Infrared thermography is an effective tool in evaluating building's thermal performance when there is a reasonable temperature gradient between indoor and outdoor temperatures. This paper presents a novel approach of using low-resolution infrared camera with a single point heating system from which the thermal conductivity and thermal insulation of building's wall can be categorised and estimated. An experimental study has been conducted on different sample wall sections and Artificial Neural Network is used to analyse the infrared images of walls for categorisation based on the level of wall insulation. The results show significant accuracy in categorising the wall types based on their level of insulation from a set of infrared images.

Keywords: U-value, Artificial intelligence, Neural Network, Infrared Thermography, Insulation.

1. Introduction

It is necessary to develop strategies for reducing the energy consumption due to space heating of residential buildings. Retrofitting an existing building with improved wall insulation can reduce heat loss through the building's walls and consequently energy consumption for space heating. However, before the retrofitting, it is necessary to identify the current level of insulation, which is the U-value of the building's wall. The designed U-value of a building's wall is calculated as the reciprocal of the summation of thermal resistances of different layers of the wall [1].

$$U = \frac{1}{R_i + \frac{d_1}{k_1} + \frac{d_2}{k_2} + \cdots \ldots\ldots\ldots + R_e} \qquad (1)$$

Here, U is the U-value of the wall, k is the thermal conductivity of the materials in different layers of the wall, d is the thickness of the wall layers, R_i and R_e are the thermal resistance of air at internal surface and external surface respectively. To determine the U-value of an existing building's wall using equation (1), thermal conductivities of different layers of the wall are required to be determined. It can be done by conducting laboratory test on the samples collected by drilling the walls; which is a damaging process. There are several devices available to measure U-values of test specimen in laboratory; however, these often differ as high as 30% from the in-situ U-value [2]. There are two non-invasive methods existing for in-situ U-value measurement namely Heat Flux Meter (HFM) method and Infrared Thermovision Technique (ITT). Both techniques have their own limitations in relation to accuracy, time and environmental conditions. To overcome the limitations this paper proposes a novel approach for the categorisation of buildings' wall insulation based on the U-value by combining thermal images of walls and artificial intelligence with the application of single point heat source.

2. Methodology

An uninsulated wall has a high U-value and most of the applied heat will pass through it. Conversely, an insulated wall has a low U-value and most of the applied heat will disperse over the internal surface. The difference in the thermal response, while applying a point heat in the internal side of a test wall for a certain period, can be observed by monitoring the wall using a low-resolution infrared camera. The schematic diagram of the experimental set up is shown in Figure 1-a. The thermal profile generated from the infrared images is used to train an Artificial Neural Network (ANN) for categorisation of the wall type. ANN consists of neurons organised in layers which mimic the thinking process of a human brain. ANN can be trained to learn certain features of a data set, and based on the learning it can predict the output of a similar unknown input. Figure 1-b shows the architecture of a typical ANN. The experiment work is conducted twice on each wall type so that the data obtained from the first run of experiment could be used for training the ANN and the data obtained from the second run of experiment can be used to test the network performance.

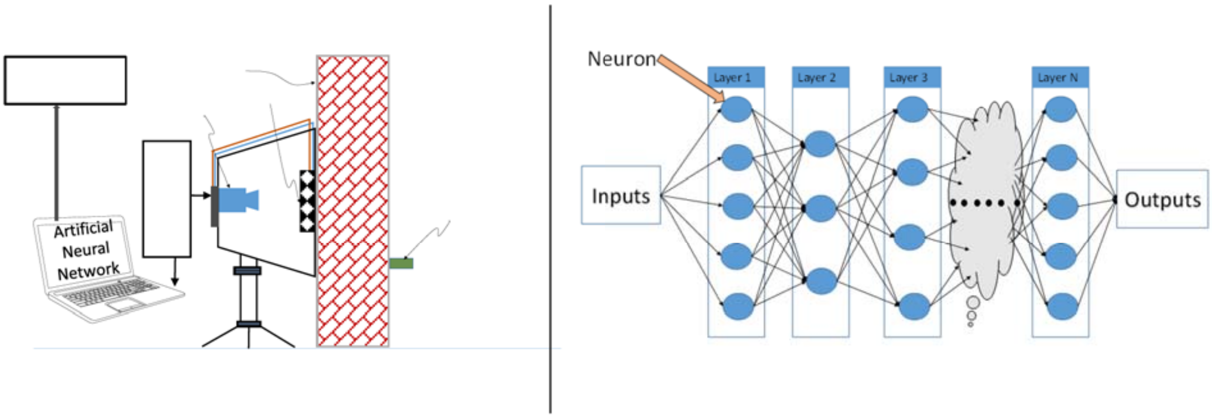


Figure 1: (a) Schematic diagram of experimental set up. (b) The architecture of a typical ANN

3. Experimental work

The experiments are conducted on four different wall samples made of brick, brick with external insulation, concrete block and concrete block with external insulation. EcoTherm board with a thickness of 100 mm is chosen as the external insulation for these walls. A plastic box fitted with a diesel engine glow plug attached to the internal side of the wall is used, combined with IRISYS 1002 infrared camera as in Figure 1-a. The glow plug acts as a point heat source and the infrared camera is set to capture 16x16 pixel infrared images at five seconds interval for about an hour. The glow plug's tip temperature as well as the ambient temperature are recorded with a K-type thermocouple and NI USB-TC01 data acquisition system at one second interval.

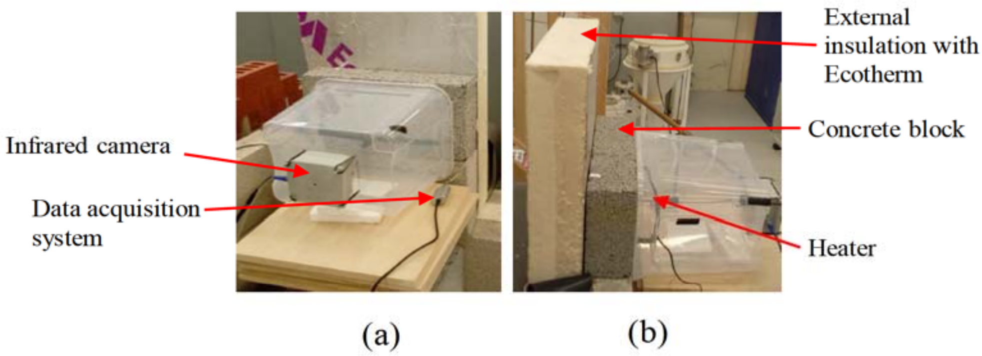
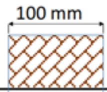
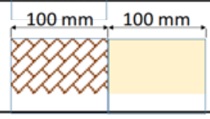
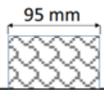
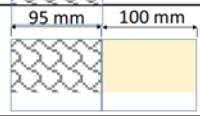


Figure 2: Experimental work on C1 sample wall

Figure 2-a and Figure 2-b show the experimental work on one of the samples. The sample walls are represented as A1, B1, C1 and D1 for the first run of experiment and A2, B2, C2 and D2 for the second run of experiment. The properties of the sample walls are presented in Table 1. The U-value of the sample walls are calculated using equation (1) where the values of R_i and R_e is considered as 0.13 and 0.04 respectively [3]. The thermal conductivity of brick wall is taken as 0.27 W/mK [4], the thermal conductivity of concrete block is considered as 1.5 W/mK [5] and the thermal conductivity of the Ecotherm is 0.022 W/mK [6].

Table 1: Properties of wall sample used in the experiments.

Sample Number	Material	Thickness (mm)	Thermal Conductivity (W/mK)	U-value (W/m^2K)	Schematic view of sample wall
A	Brick	100	0.27	1.86	
B	Brick insulated externally with Ecotherm	100+100 =200	0.27 & 0.22	1.01	
C	Concrete block	95	1.5	4.29	
D	Concrete block insulated externally with Ecotherm	95+100 = 195	1.5 & 0.22	1.45	

4. Results and Discussion

Sample D1 and D2 has lower U-values than sample C1; therefore, it is expected that the temperature profile of D1 and D2 will be higher than that of C1. The temperature profile of D2 is clearly higher than that of C1 in Figure 3-a. However, the temperature profile of D1 is marginally higher than that of C1 in Figure 3-b, because the ambient temperature was higher during the time of conducting experiment on C1 than on D1.

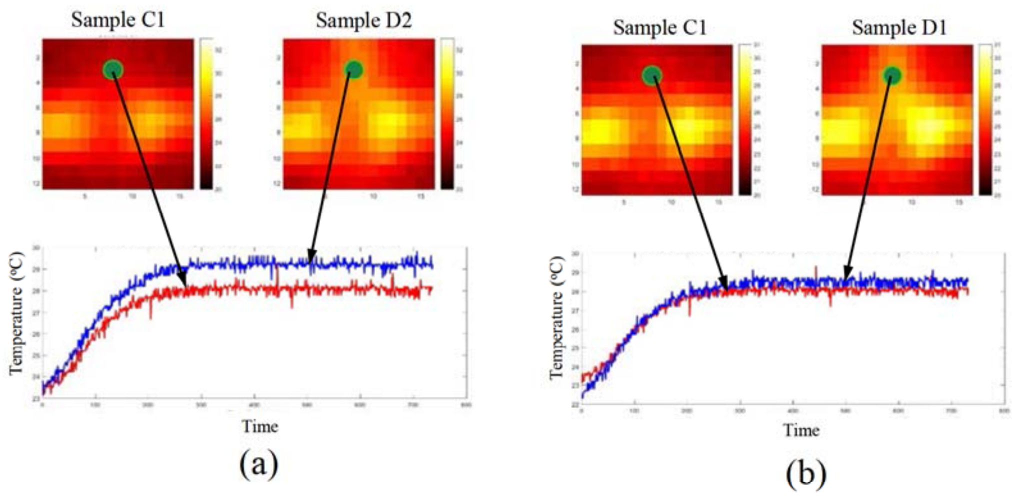


Figure 3: Comparison of temperature profiles (a) sample C1 and D2, (b) C1 and D2

It is also found that the rate of temperature increase with time is higher in sample D1 and D2. Therefore, it is assumed that ambient temperature has a significant influence on the thermal profile and derivative of thermal profile is a key parameter to identify the characteristics of the thermal profile. Considering these assumptions, three modified profiles namely T^a, T^b and T^{ab} are developed, which are presented in equation (2), (3) and (4)

$$\boldsymbol{T}^a_{(i,j,k)} = \boldsymbol{T}_{(i,j,k)} - \boldsymbol{T}^{ext}_k \quad (2)$$

$$\boldsymbol{T}^b_{(i,j,k)} = \sum_1^k \left[\boldsymbol{T}_{(i,j,k+1)} - \boldsymbol{T}_{(i,j,k)}\right] \quad (3)$$

$$\boldsymbol{T}^{ab}_{(i,j,k)} = \sum_1^k \left[\boldsymbol{T}^a_{(i,j,k+1)} - \boldsymbol{T}^a_{(i,j,k)}\right] \quad (4)$$

Here $T_{(i,j,k)}$ is the original temperature value at pixel *(i,j,k)* on infrared image, $T^a_{(i,j,k)}$ is the modified temperature value of pixel *(i,j,k)* on infrared image, $T^b_{(i,j,k)}$ is the cumulative temperature difference at pixel *(i,j,k)*, $T^{ab}_{(i,j,k)}$ is the cumulative temperature difference of profile T^a and T^{ext}_k is the external temperature at the time of capture of the corresponding infrared image. A feed forward neural network with *softmax* layer is developed using pattern recognition app of MATLAB to categorise the wall types with profile T^b, T^{ab} and their standard deviations as the input parameters and wall type as the output parameters.

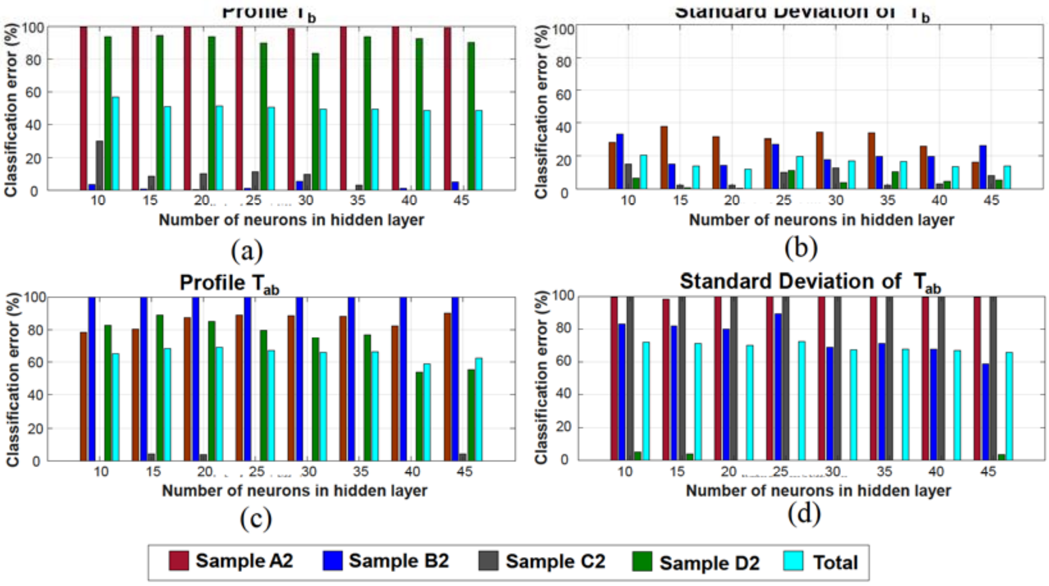


Figure 4: Percentage error of categorisation

Figure 4-a to Figure 4-d represent the percentage error in categorising the samples A2, B2, C2 and D2 with 10 ,15, 20, 25, 30, 35, 40 and 45 neurons in hidden layer. It is found that the standard deviation of profile Tb shows the least percentage error compare to other profiles. The probable reason for that is the standard deviation represents the dispersion in thermal profile more significantly than the profile itself. Profile Ta was developed by deducting the ambient temperature from the original temperature profile, which probably reduced the variation that characterise the temperature profile; and hence the percentage error in categorisation from profile Tab and the standard deviation of Tab become very high. It is also found from Figure 4-b that ANN with 20 neurons in hidden layer gives the lowest total error which is 12% with the error in detecting A2, B2, C2 and D2 are 31%, 14%, 2% and 0.33% respectively.

5. Conclusion

Retrofitting of residential buildings with improved wall insulation could significantly reduce the energy consumption for space heating; however, in-situ U-value of walls should be considered before retrofitting as over insulation could be expensive with low payback period. The existing methods of U-value estimation have some limitations. Therefore, a novel approach is proposed to categorise a building's wall based on the U-value by combining thermal image and ANN with the application of point heat. The result shows the suitability of feed forward neural network in categorisation of walls from thermal profile developed by analysing thermal images. ANN with 20 neurons in hidden layer achieved 88% overall classification accuracy with a minimum 69% for any particular wall type.

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