Thermal performance evaluation of a fabricated multilayer insulation blanket and validity of Cunnington-Tien correlation for this MLI

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Abstract: *The intention of this paper is to discuss the results obtained from tests conducted at Amirkabir University of Technology Thermal Control Lab on multilayer insulation (MLI) blankets designed and fabricated in university, describing the thermal performance of test specimens at two environmental temperatures. We have evaluated the MLI performance by experimentally measuring our MLI's emissivity factor. For this purpose we have defined our experiments based on the effective emissivity model. Fabricated MLI blankets are tested in a vacuum chamber at an approximate pressure of 10^{-6}mbar and temperatures of approximately 30°C and -70°C, while subjected to heat with the power input in the range of 1.0 to 2.5 Watts. Results show that the measured effective emissivity is within the range of other reported experimental data. Having determined the effective emissivity of the MLI, one can calculate the heat flux passing through the MLI during the test period. As a result the variation of this heat flux with the temperature of hot surface can be plotted. This result provided us the opportunity to evaluate the validity of Cunnington-Tien correlation for our fabricated MLI blankets. Our study shows that the heat flux passing through the fabricated MLI predicted by Cunnington-Tien correlation agrees reasonably with the that calculated using empirical data.*

1. Introduction

One of the most serious challenges facing designers of a satellite is maintaining the temperature of intended hardware within acceptable limits in the harsh environment of space where temperatures in a wide spectrum from -250 ^{o}C to +300 ^{o}C are frequently encountered due to solar radiation, Albedo and earth radiation (Gilmore, 2002). Satellites in this respect are quite vulnerable to environmental fluctuations due to their relatively small size which makes incorporating waste heat disposing systems quite challenging. Of many available solutions to this problem, use of multilayer insulation systems (MLI) nowadays is considered canonical. Compared to other solutions, their light weight and relative ease of manufacture are key points as viewed by satellite designers.

The usual structure of a multilayer insulation system comprises a number of thin shields (outer cover and inner covers) of very low infrared (IR) emissivity made of aluminized Beta cloth in the case of outer cover and aluminum coated layers of thin plastics (Mylar or Kapton) in the case of inner layers characterizes by high mechanical strength and low thermal conductivity. These thin sheets are separated by low conductivity spacers usually fabricated of polyester or nylon netting or silk (Gilmore, 2002; Finckenor and Dooling, 1999; Henninger, 1984). Complexities associated with the task of modeling heat transfer through multi layer insulation systems due to the unpredictable variation of properties (e.g. contact pressure, interstitial pressure), their anisotropic properties and complex three dimensional effects, to name a few, make this task a formidable one(Fesmire et al., 2002;Krishnaprakas et al., 2000, Cunnington and Tien, 1970).

As a result, numerous empirical correlations and test methods have been developed to facilitate modeling heat transfer for engineering applications (Chorowski et al., 2000; Bapat et al., 1990). Table 1 from Bapat et al. (1990) provides a brief review of existing correlations. It must be noted that these correlations sometimes neglect phenomena such as heat transfer by gas conduction or temperature dependence of properties and therefore, while providing a valuable resource, their application is limited only to special MLI configurations. As a result, thermal control engineers must practice extra care in applying any of the mentioned correlations to their own problems. Another way of addressing the problem of modeling heat transfer through MLI blankets is to use existing empirical data and observe the trends but this approach, again, has the drawback of being applicable only to the designs that are similar to the ones which provided the experimental data (Fesmire and Augustynowicz, 2004; Dufay et al., 2001; Chau and Moy, 1971). So, due to lack of experimental data available to satellite designers, not to mention unreliability or inaccuracy, there is no way to corroborate the viability and accuracy of abovementioned methods in different multilayer insulator blanket configurations (e.g. high leakage, seamed, etc) but with experiment. In other words, viability of each correlation for a certain MLI configuration can only be approved through experimental investigation. The present paper discusses the results of tests that are conducted to evaluate the effective emissivity of the MLI blankets employed in a simple configuration, , in an effort to simulate space conditions and then verify whether the Cunnington-Tien correlation(Bapat et al., 1990) provides accurate predictions of MLI blankets' performance when employed in such arrangements or not . The results of these experiments will enable thermal control engineers to apply this correlation confidently to similar configurations

The method employed to evaluate effective emissivity, a crucial parameter representing thermal performance of MLI blankets, in these series of tests will be given a brief treatment in section 2. A brief review of the Cunnington-Tien correlation is also provided to familiarize the reader with its application. Details of test facility and experimental setup are given in following sections.

2. Theoretical Remarks

The main method of obtaining data in the tests conducted is to record temperature variations of certain surfaces while exposed to a uniform heat flux over a period of time. Having the respective data, it is possible not only to evaluate effective emissivity, but to plot heat flux versus temperature variations and compare these curves with the ones provided by the Cunnington-Tien correlation to assess its accuracy. In order to describe how the effective emissivity is calculated for the test subjects, the effective emissivity heat transfer model is given a brief treatment in what follows. Also, a general form of the Cunnington-Tien correlation which contains both solid conduction and radiation contribution to heat transfer will be presented.

2.1 Effective emissivity model (ε_{eff} – model)

Due to wide usage of ε_{eff} model in special software applications employed by satellite designers, this model will receive a more delicate elaboration in this paper. This approach considerably reduces the complexity in the temperature calculations [2, 3]. The effective emissivity of a MLI blanket is usually calculated according to the following relationship with the assumption that gas conduction effects are negligible at pressures of approximately 10 $^{-5}$ mbar. (Gilmore, 2002; Lin et al., 1995)

$$\varepsilon_{eff} = \frac{Q}{A\sigma(T_H^4 - T_C^4)} \qquad (1)$$

Where σ is the Stefan – Boltzman constant (5.67*10^{-12} W/ cm^2 K^4), A is the area of the surface of the blanket considered (m^2), Q is the net heat transferred in Watts and ε_{eff} is effective emissivity for each test specimen. T_H and T_C represent hot and cold surface temperatures respectively. These temperatures can be interpreted differently based on the particular configuration that is modeled (Lin et al., 1995). These interpretations in turn affect the definition of ε_{eff} factor and numerical accuracy of the calculations. Three of the most common configurations encountered in spacecraft applications form the basis for the following interpretations of the terms used in Eq.1. Geometrically, three methods have found widespread for attaching MLI blankets to surfaces. If the MLI blanket is wrapped tightly around the hardware, then the surface area of the blanket will be the same as the hardware's, as can be seen in Fig.1 (a). The other configuration involves leaving a relatively small gap between the surface of the hardware and inner layer of the MLI blanket, as depicted in Fig. 1(b), to incorporate materials for specific purposes; see Lin et al., 1995 for more details. The configurations based on third method are comprised of a MLI blanket draped with a substantial distance over the hardware, as illustrated in Fig.1(c). and associated connectors which fix the blanket to the surface of the hardware such hook and pile connections.

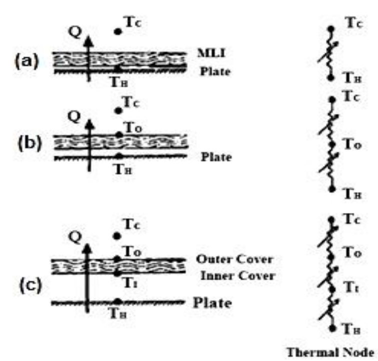


Fig. 1. Modeling of Hardware-MLI configurations and the associated ε_{eff} definitions (Lin et al., 1995)

It must be noted that the specific configuration studied in this paper resembles the third method of installing MLI blankets over the desired surfaces. This configuration has been the most widely employed geometry in spacecraft applications [1]. Based on this configuration T_H, T_C, and A in Eq. 1 are hardware temperature, cold wall temperature, and hardware area, respectively. In order to calculate ε_{eff}, a more precise version of Eq. (1) is used in the form of (Thomas, 1980):

$$q = \frac{(\frac{\varepsilon_i}{\alpha_i})\sigma T_H^4 - (\frac{\varepsilon_j}{\alpha_j})\sigma T_C^4}{\frac{1-\alpha_i}{A_i\alpha_i} - \frac{1}{A_i F_{i-j}} - \frac{1-\alpha_j}{A_j\alpha_j}} \quad (2)$$

Where F_{i-j} refers to view factor from surface i to surface j. Subscripts i and j correspond to "hot" and "cold" surfaces, respectively, and ε_i is the parameter sought, .i.e. effective emissivity or ε_{eff}. In the preceding relation, geometric (configuration) factors are calculated according to the relations derived by Ehlert and Smith (Ehlert and Smith, 1993). T_H and T_C correspond to the temperature of test plates covered with MLI blanket between which the planar heater is sandwiched (for more details refer to section 3, test facility and setup) Moreover, in this experiment, ε and α can be assumed equal due to the fact that the tests are carried out in IR range. As the expression of Eq.2 only counts for the heat transfer between two surfaces, the total heat transfer, which in the experiments conducted equals the heat dissipated by the electric heaters, has to be calculated as the summation of radiation exchanges between all of the test hardware faces covered by MLI blanket and the surrounding walls (test facility details are provided in section.3). As a result, equation (2) can be written in the following form

$$q_{heater} = \sum_{n=1}^{6} q_{n,MLI} = \sum_{n=1}^{6} \frac{\sigma(T_H^4 - T_C^4)}{\frac{1-\varepsilon_{eff}}{A_H\varepsilon_{eff}} - \frac{1}{A_H F_{H-MLI}} - \frac{1-\varepsilon_n}{A_n\varepsilon_n}} \quad (3)$$

Where ε^* is the effective emissivity (ε_{eff}) of multilayer insulation blanket. The subscript n refers to the black surfaces of vacuum chamber in which test subject is suspended. A corresponds to the total area covered by MLI blankets and F is the geometric factor from the MLI blanket surface. Also q is the heat dissipated by planar heater through MLI blanket which is covering metal plates surrounding the heater. Calculation of the dissipated energy is straightforward according to the following relation

$$q = IV = V^2/R \quad (4)$$

Where q is the dissipated energy in Watts, R the electric resistance of the heaters, V the potential applied to heaters in Volts and I is the electric current applied to heaters measured in Amperes.

2.2 Cunnington and Tien model (CT-model)

CT-model treats the heat transfer through MLI as the sum of separate conductive and radiative contributions and it takes into account the effects of temperature dependence of properties (Krishnaprakas et al., 2000). The expression depicting heat flux by this model is

$$q = \frac{P_C^d l a_1 (T_H^{1+b_1} - T_C^{1+b_1})}{N(1+b_1)(1+t)N_C} - \frac{2n^3\sigma l a_2 (T_H^{4+b2} - T_C^{4+b2})}{N(4+b_2)(1+t)} \quad (5)$$

in which the P_c is the pressure due to compression, d is the exponent of P_c, l the spacer thickness, t the shield thickness, n the refractive index of the spacer medium, N the total number of complete layers of shield and spacer, and T the temperature. Other parameters a_1 and b_1 are used to express the temperature dependence of a parameter C associated with the evaluation of conduction through solid as

$$C \approx a_1 T^{b_1} \quad (6)$$

Similarly, parameters a_2 and b_2 are used to express the emissivity of metal coating on shield as

$$\varepsilon \approx a_2 T^{b_2} \quad (7)$$

Based on the properties of the MLI blanket fabricated at Amirkabir University of Technology Thermal Lab, value of $b_1=1$ is chosen. Also according to correlation given by Chau and Moy (Chau and Moy, 1971), which is in the following form,

$$\varepsilon = 6.337\times10^{-4}\, T^{2/3} \quad (8)$$

a value of $b_2=0.67$ is assumed here. As a result, according to Eq.6 and Eq.7, Eq.5 can be written in the following form

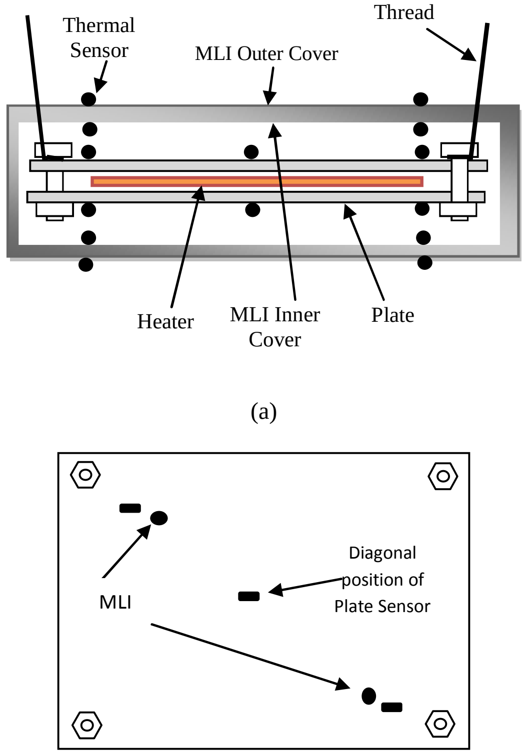
$$q = c_1\,(T_H^{2}-T_C^{2}) + c_2\,(T_H^{4.67}-T_C^{4.67}) \quad (9)$$

where c_1 and c_2 are constants in the conductive and radiative terms, respectively. Eq.5 through Eq.7 and their simplified version, Eq.9, will be used later to compare the data obtained from the experiments with the estimations by Cunnington-Tien (CT) model.

3. Test facility and setup

The experiments to evaluate the thermal performance of fabricated MLI blankets have been conducted at Thermal Control Lab of Amirkabir University of Technology and mainly by the help of its vacuum chamber, that is capable of delivering temperatures from -80°C to +100°C, and pressures as low as 10^{-6} mbar. Exept the base plate of chamber which is polished with emissivity of 0.1, all inner walls of the chamber are black painted with emissivity of 0.9. The test model consists of planar heaters sandwiched by two aluminum plates, completely covered by MLI blankets as can be seen in Fig.2 (a). 14 thermal sensors, are installed on and under MLI blankets to collect temperature data, six of them are installed diagonally on each of the aluminum plates in a manner depicted in Fig.2 (a) and (b).

Specifications of the heaters employed in this experiment, are enumerated in Table 1.



(a)

(b)

Fig. 2. a- The test model configuration, b- Sensors distribution over aluminum plate

Table 1
Specifications of the heaters used in the experiments

Dimensions	Number of heaters used in experiment	Electric resistance
76.2*76.2 mm	2	294 Ω
101.6*203.2 mm	1	318 Ω

The planar electric heaters are installed between aluminum plates in the configuration depicted in Fig.3. The power output of each heater is selected in a manner to have uniform heat flux over aluminum plates. Very small difference between the temperatures along the plate sensors verifies this uniformity of heat flux.

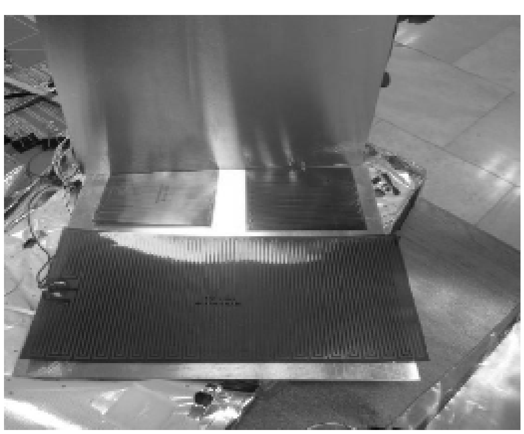


Fig. 3. Array of electrical heaters installed between aluminum plates

The plates are connected together by 4 screws and paper clips as shown in Fig.4.

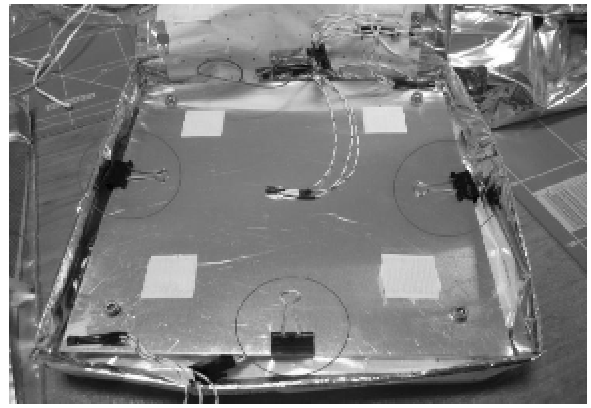


Fig. 4. Connection between plates is maintained by screws and paper clips

Fig.4 also demonstrates how thermal sensors are installed on MLI blankets by the means of thermally conductive adhesives. Eventually the whole complex is suspended in the vacuum test chamber by means of special threads. Thermal sensors are also installed on the surfaces of vacuum chamber's inner walls to insure accuracy in temperature measurements.

Although MLIs are normally exposed to deep space with temperatures as low as 4 Kelvin, but due to limitations of the vacuum chamber employed, as stated before, the lowest maintainable temperature in the test chamber is -80°C.

4. Test plan, Results, and discussion

To achieve the goals of this paper, mentioned before, two tests were designed, one with cold chamber wall and the other with hot chamber wall. Temperature data were measured using 14 sensors. The acquired data were analyzing to evaluate MLI performance and the validity of CT-model in the present study.

Power input to the heaters should be adjusted carefully to avoid temperatures of MLI and heaters rising beyond their limits. Based on the heaters specifications a temperature limit of 100 C is considered in our tests. To find out the power input limit of heaters a variety of tests were conducted for different power inputs under atmospheric and vacuum pressures in the chamber. As a result, the maximum power input allowed in the following experiments was set to 2.25 Watts.

4.1 Cold Wall Test

In this test the temperature of chamber wall, i.e. T_C in Eq. 2, is set equal to -69° C. The test model was suspended in the middle of chamber by means of four pieces of thread and the power input of heaters was set to be 2.25 Watts. Temperature data, measured by sensors, were recorded every 5 minutes. Temperature variations with time measured by 14 sensors are plotted in Fig.5. As seen, steady state is achieved after about 20 hours which is 5 times more than the time needed to achieve steady state in atmospheric pressure.

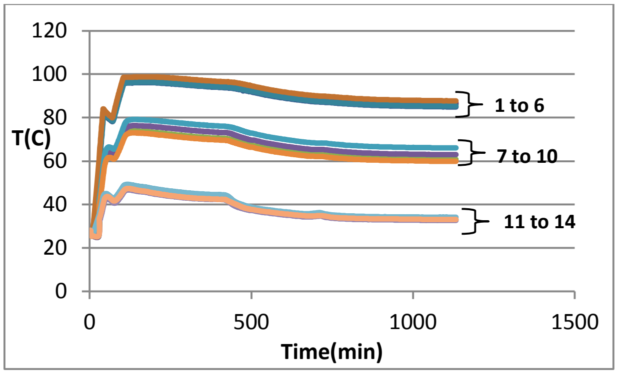


Fig. 5. Variation of MLI blanket and aluminum plate's temperatures (°C) with time for cold wall test – Sensors' locations are specified in Table 2– Heaters' power input: 2.25 W

Table 2
Sensor locations in test model

Curve Number	Sensors Locations according to Fig.3
1 to 6	On both plates
7 to 10	MLI Inner Cover
11 to 14	MLI Outer Cover

In order to evaluate the effect of hot plate temperature, TH in Eq.2, on MLI performance this cold wall test was repeated with a heater power input of 1.5 Watts. The calculated effective emissivity is reported in Table 4.

4. 2 Hot Wall Test

In this hot wall test, the temperature of chamber wall increases to 30 C and the heater power input is held equal to 1 Watt. Other parameters were similar to the ones in the previous test. Note that with a hot wall temperature 2.25 Watts heater power input results in a plate temperature rising higher than 100 C. Therefore a low heater power input of 1 Watt is set here. Again temperature variations with time measured by 14 sensors are plotted in Fig.6.

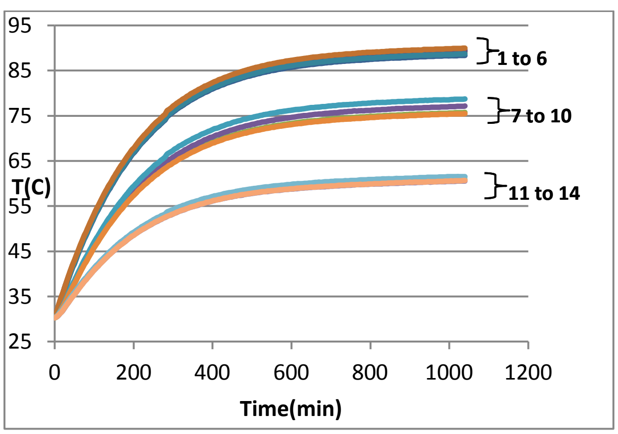


Fig. 6. Variation of MLI blanket and aluminum plate's temperatures (°C) with time for hot wall test - Sensors locations specified in Table 2– Heaters' power input: 1 W

Now, effective emissivity ε_{eff} can be calculated using Eq.3. Steady state temperatures of T_H, T_C, and heater input power are known from experiment. Other data, needed in this equation, including emissivity, the area of chamber walls and the area of MLI blanket are known as well. View factors are calculated using standard formulations. With this data the resulted nonlinear equation is solved using a numerical solver to determine the effective emissivity of tested MLI in each test case. Note that T_H is in fact the temperature averaged between sensors numbered from 1 to 6.

Table 3
Effective emissivity of tested MLI calculated from experimental data under cold and hot wall conditions

Input power (W)	Average hot plate temperature (°C)	Average wall temperature (°C)	Effective emissivity
2.25	86.2	-68.3	5.558×10^{-3}
1.5	50.2	-69.2	6.040×10^{-3}
1.0	89.1	+30.1	4.183×10^{-3}

As it is clearly seen in Table.3, the effective emissivity for our 20 layer MLI blanket is in order of 10^{-3}. Calculated values of effective emissivity in our test cases are within the range of experimental data reported in Refs.[1] and [15] (Gilmore,2002; ECSS handbook, 2011). According to these references the effective emissivity of a 20 layer MLI is between 0.003 and 0.006. Therefore, it can be concluded that for the conditions under which our tests are conducted the fabricated MLI is performing well, and can be used practically.

Comparison of results obtained for two cold wall tests show that increase of hardware (plate) temperature has positive effect on the on MLI performance. In addition, for an approximately constant hardware (plate) temperature, increase of cold wall temperature has positive effect on MLI performance.

4.3 Validity of Cunnington and Tien Correlation

The intention of this section is to investigate whether the predictions of CT-Model with respect to heat flux for the specific geometry studied in this paper, fall within reasonable limits of empirical data processed with effective emissivity model or not. To this end, variations of heat flux through MLI blankets are calculated employing effective emissivity model of Eq. 3, and then compared with the ones obtained from CT correlation, i.e. Eq. 9. Calculation of heat flux is accomplished by employing Eq.3 where T_H and T_C are obtained from experiments conducted and effective emissivity of the MLI blankets (ε_{eff}) calculated empirically in section 4.2. Prediction of heat flux using CT correlation is carried out by substituting the respective values for T_H, T_C, and the coefficients C_1 and C_2 in Eq.9. For the values of C_1 and C_2, specifications of the MLI listed in Table 4 and definition of C in equation (6) are used to assign values of 1.315×10^{-4} and 1.05×10^{-16} respectively.

Table 4
Corresponding specifications of the tested MLI blanket

MLI Specifications	Values
Inner shield thickness	0.0074 mm
Outer shield thickness	0.1000 mm
Spacer thickness	0.0500 mm
Number of complete layers of shield and spacer	20

To examine the concurrence of CT correlation with test results the heat dissipated (q) through the MLI is plotted versus plate temperature (T_H) in Figs. 7 and 8. Comparison of results in these figures would provide a measure of relative accuracy of this model, which in turn infers the suitability of using CT correlation for the fabricated MLI under the present test conditions.

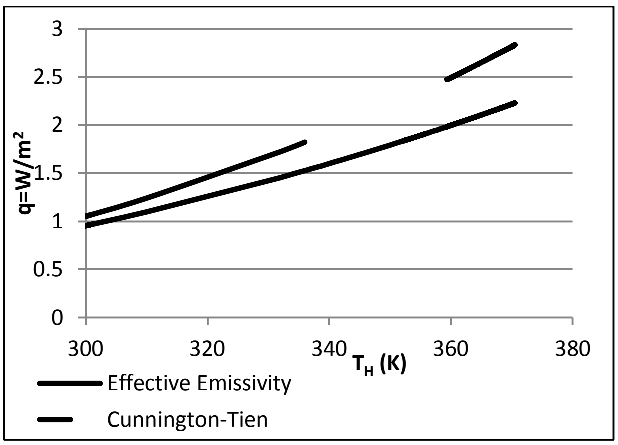


Fig. 7. Variation of heat flux passing through the MLI blanket versus hot plate temperature- Heaters' power input: 2.25 W

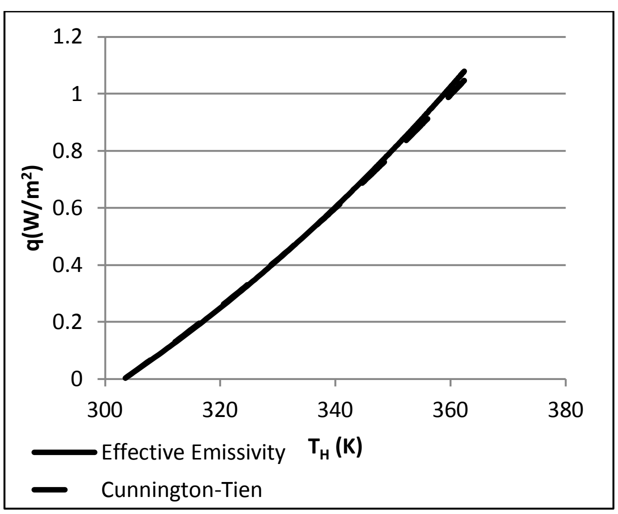


Fig. 8. Variation of heat flux passing through the MLI blanket versus hot plate temperature - Heaters' power input: 1.0 W

According to Fig.7 and Fig.8, results calculated from the effective emissivity model using experimental data are in an acceptable agreement with the results obtained from Cunnington – Tien correlation. However, analysis of the test data indicates that an average error of 4% for the 1 Watt case and 21% for the 2.25 Watt case exist. In both figures, the difference between results increases as the heat flux passing through the MLI increases. This effect can also be observed by comparing two figures with each other. As seen the error substantially decreases in the hot wall case where the level of heat flux passing through the MLI is decreased.

5. Conclusion

The goal of this paper was to study the performance of a fabricated MLI and to evaluate the validity of Cunnington–Tien correlation for this MLI. Base on the experiments conducted in this work, it was shown that effective emissivity of the fabricated MLI falls within the range reported in the other references. Based on this fact, we concluded that this type of MLI is performing well, and can be used for our experimental researches. Moreover, it was demonstrated that Cunnington–Tien correlation is applicable here to predict the heat flux of MLI in the temperature range of less than 100 C with an acceptable accuracy. It was also observed that for lower heat fluxes of MLI the accuracy of Cunnington–Tien correlation in predicting heat flux clearly increases.

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