THERMAL DOUBLER MODEL

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Abstract.

This work aims to develop a mathematical model to evaluate rectangular thermal doubler and its heat transfer capabilities. Such model is intended to be an useful tool for engineers during the preliminary stage of satellite design in order to support the decision process regarding the heat transfer technique. This model was developed by finite volumes and a sensibility analysis was performed to explore the effects of rectangular doubler dimensions on the final temperature of thermal doubler. The results provided by this model have been physically coherent. The sensibility analysis indicated that there is a specific combination of doubler dimensions that provides a positive correlation between weight and heat transfer capability.

***Keywords**: Thermal Doubler, Heat Transfer and Satellite Thermal Control.*

1. INTRODUCTION

Thermal doublers are heat transfer devices manufactured with materials with high thermal diffusivity such as metallic alloys and carbon composites. They are used to increase the heat transfer between a heat source and a heat sink by increasing the heat transfer area.

Thermal doublers are applied when high heat transfer rates (greater than 1Watt/inches^2) in very small areas are identified. This situation is very usual in aerospace application such as satellites and aircraft. Its application is a positive contribution to reduce the costs to launch a satellite or to accomplish an aircraft flight mission.

For satellites application, heat transfer is mainly driven by conduction with portion of radiation phenomena. For aircraft (models with ceiling altitude around 41,000 ft), thermal doublers heat transfer is still driven by conduction phenomena with portions of convection and radiation.

Due to its physical characteristics (mainly low weight and high thermal diffusivity) and due to economical advantages for aerospace (such as low design and maintenance costs, good reliability and positive contribution for reduction of fuel consumption), thermal doublers application is an option to be considered during the cooling design of electronic equipments.

Satellites developed by the partnership between Brazil and other countries are equipped with thermal doublers, however, the design of this device was not developed by Brazilian engineering team. The scenario presented above is the reason to study thermal doublers.

This paper will address a specific rectangular thermal doubler for satellite application and all the steps of model construction as well as the sensibility analysis focused on doubler dimension and heat transfer capabilities. In this application, the component over thermal doubler is enabled when satellite is in orbit, only.

2. THERMAL DOUBLER INSTALLATION

Thermal doublers are installed over surfaces at low temperatures (heat sink surfaces). Usually, the heat sink surfaces are made by composite materials that have low weight and appropriated mechanical properties for aeronautics application.

For this specific application, thermal doubler will be installed on the external side of satellite as presented in Fig.1 which is not in scale.

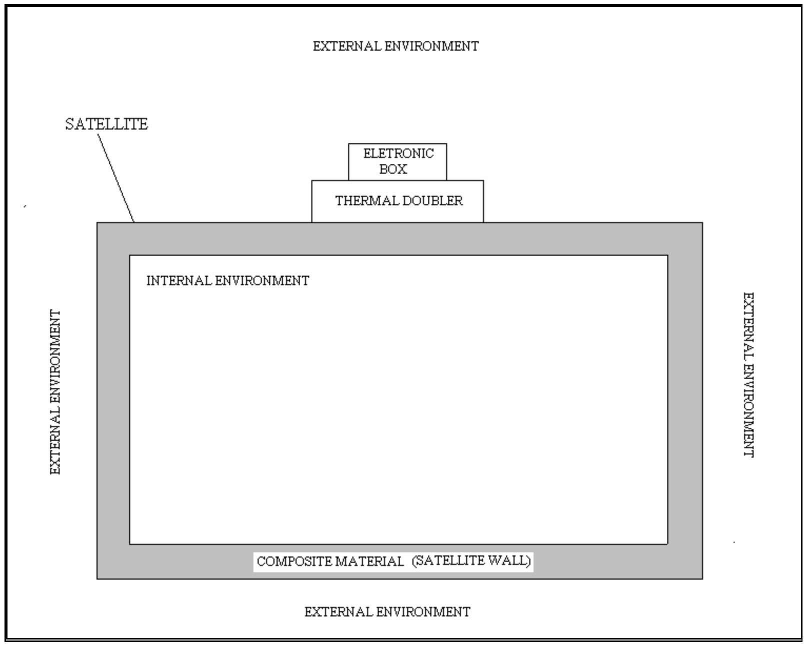

Figure 1. Section view of thermal doubler installation to be modeled.

3. MATHEMATICAL MODEL

Mathematical model construction consists in determining: the physical sketch of physical installation, the boundary conditions and the physical modeling by equations.

3.1 Sketch of model and boundary conditions

Sketch of thermal doubler, model equations and boundary conditions are presented in the next subchapters.

3.1.1. Sketch of model

The physical sketch is presented in Fig.2.

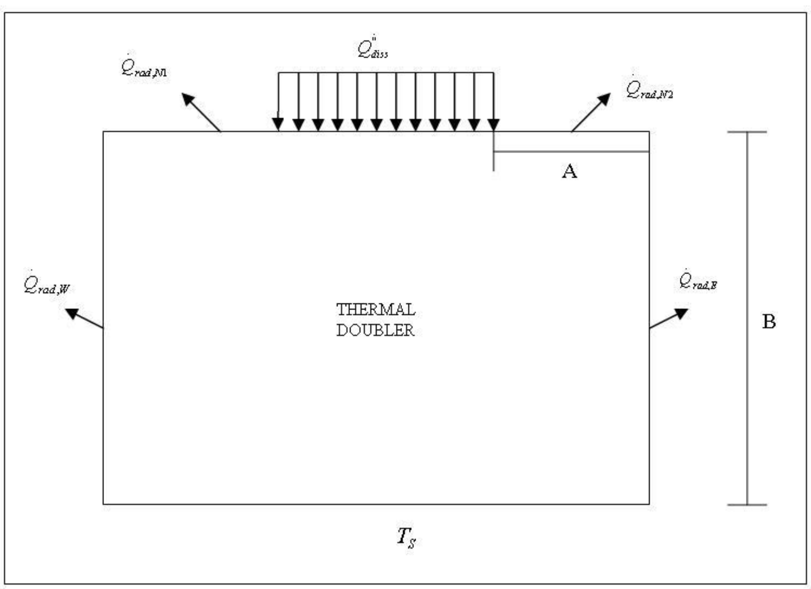

Figure 2. Physical sketch of rectangular thermal doubler and its boundary conditions

3.1.2 Physical Modeling by Equations

The following assumptions were considered for the rectangular thermal doubler modeling:

- Steady state condition;
- No heat generation inside of thermal doubler;
- Uniform conductive heat transfer coefficient;
- Temperature of external environment is uniform;
- Temperature is uniform on the South face of thermal doubler;
- Emissivity is uniform on the surfaces where radiation heat transfer exists;
- Heat flow is symmetrically located and uniformly distributed on the central portion of North face of thermal doubler.

The balance energy in steady state condition applied to continuous rectangular thermal doubler is presented below:

$$\dot{Q}_{diss} - \dot{Q}_{rad,N1} - \dot{Q}_{rad,N2} - \dot{Q}_{rad,W} - \dot{Q}_{rad,E} - \dot{Q}_{cond,S} = 0 \tag{1}$$

where:

$$\dot{Q}_{diss} = \dot{Q}''_{diss}\, A_{diss} \tag{2}$$

$$\dot{Q}_{rad,N1} = \varepsilon\sigma A_{N,1}(T_{BN}^4 - T_{amb}^4) \tag{3}$$

$$\dot{Q}_{rad,N2} = \varepsilon\sigma A_{N,2}(T_{BN}^4 - T_{amb}^4) \tag{4}$$

$$\dot{Q}_{rad,W} = \varepsilon\sigma A_{W}(T_{BW}^4 - T_{amb}^4) \tag{5}$$

$$\dot{Q}_{rad,E} = \varepsilon\sigma A_{E}(T_{BE}^4 - T_{amb}^4) \tag{6}$$

$$\dot{Q}_{cond,S} = \varepsilon\sigma A_{S}(T_{BS} - T_{amb}) \tag{7}$$

3.1.3 Boundary Conditions

Heat flow transmitted to the doubler is equivalent to 100 % of energy dissipated by the component.

The emissivity value on the surfaces under radiation heat transfer are the same for North, West and East faces.

Temperature on South face is the superficial temperature of composite material; this temperature is the superficial temperature of composite material which is the same temperature of external environment.

The superficial temperature of other satellite walls is the same one of external environment.

3.2. Computational method

Finite volume is the method used for modeling the heat transfer on this rectangular thermal doubler. It consists in making the heat transfer balance in each finite volume that makes part of geometry being studied.

3.2.1. Grid Generation

Uniform and non-uniform structured grid method was selected because the geometry of rectangular doubler is appropriated for the usage of global coordinates system.

For uniform grids, it was adopted an arithmetic correlation among the volumes of control. Non-uniform grids were obtained by the geometric correlation with constant factor among the volumes of control. In both cases, the node is centered inside each volume of control.

3.2.2. Discrete equations and linearization of radiation heat transfer terms

The discrete equations for central and boarder control volumes were done accordance with the zones of rectangular thermal doublers presented in Fig. 3:

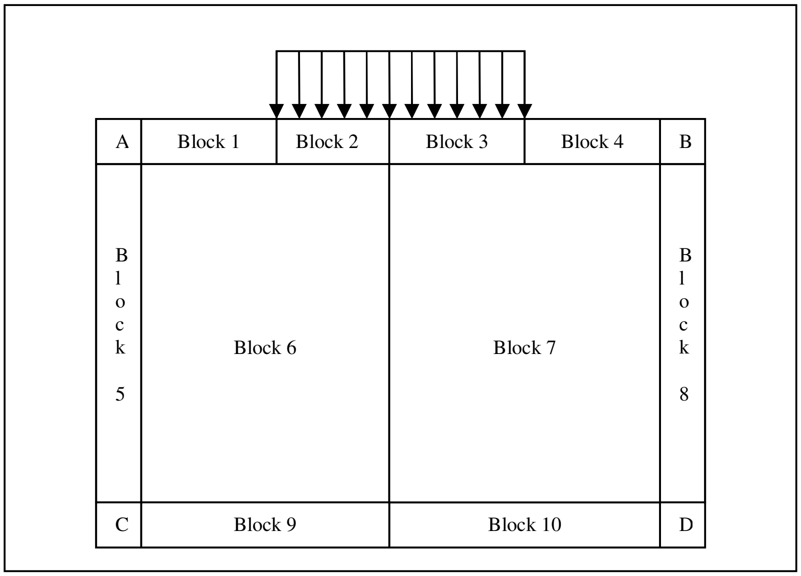

Figure 3. Blocks where the volumes of control can be located

To make the equations discrete, it was adopted the following approach to make linear the T^4 terms related to radiation heat transfer. This method was successfully applied by Castejon Garcia (1987).

$$T_1^4(y_1) = 4.T_1'^3(y_1).T_1(y_1) - 3.T_1'^4(y_1) \tag{8}$$

Where:

$T_1'(y_1)$ is the value of T on the previous iteration

$T_1(y_1)$ is the temperature being calculate by the current iterative step

Once this method is iterative, $T_1'(y_1)$ receive the values of $T_1(y_1)$ on the previous iteration. The discretized equations for each zone of thermal doubler are presented below:

For volume of control A:

$$-\varepsilon\sigma A_{N1}(T_{BN1}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_E(T_E - T_P)}{\Delta X_{EP}} - \varepsilon\sigma A_W(T_{BW}^4 - T_{amb}^4) = 0 \tag{9}$$

For volumes of control inside block 1:

$$-\varepsilon\sigma A_{N1}(T_{BN}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_E(T_E - T_P)}{\Delta X_{EP}} - \frac{kA_W(T_P - T_W)}{\Delta X_{PW}} = 0 \tag{10}$$

For volumes of control inside block 2:

$$\dot{Q}_{diss}\, A_{diss} - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_E(T_E - T_P)}{\Delta X_{EP}} - \frac{kA_W(T_P - T_W)}{\Delta X_{PW}} = 0 \tag{11}$$

For volumes of control inside block 3:

$$\dot{Q}_D\, A_N - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} - \frac{kA_E(T_P - T_E)}{\Delta X_{EP}} + \frac{kA_W(T_W - T_P)}{\Delta X_{WP}} = 0 \tag{12}$$

For volumes of control inside block 4:

$$-\varepsilon\sigma A_{N2}(T_{BN2}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_S)}{\Delta y_{SP}} - \frac{kA_E(T_p - T_E)}{\Delta X_{PE}} + \frac{kA_W(T_W - T_P)}{\Delta X_{WP}} = 0 \quad (13)$$

For volume of control B:

$$-\varepsilon\sigma A_E(T_{BE}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_W(T_W - T_P)}{\Delta X_{WP}} - \varepsilon\sigma A_{N2}(T_{BN2}^4 - T_{amb}^4) = 0 \quad (14)$$

For volumes of control inside block 5:

$$-\varepsilon\sigma A_W(T_{BW}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_E(T_E - T_P)}{\Delta X_{EP}} + \frac{kA_N(T_N - T_P)}{\Delta y_{NP}} = 0 \quad (15)$$

For volumes of control inside block 6:

$$\frac{kA_N(T_N - T_P)}{\Delta y_{NP}} - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_E(T_E - T_P)}{\Delta X_{EP}} - \frac{kA_W(T_P - T_W)}{\Delta X_{PW}} = 0 \quad (16)$$

For volumes of control inside block 7:

$$\frac{kA_N(T_N - T_P)}{\Delta y_{NP}} - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} - \frac{kA_E(T_P - T_E)}{\Delta X_{PE}} + \frac{kA_W(T_W - T_P)}{\Delta X_{WP}} = 0 \quad (17)$$

For volumes of control inside block 8:

$$-\varepsilon\sigma A_E(T_{BE}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_S)}{\Delta y_{PS}} + \frac{kA_W(T_W - T_P)}{\Delta X_{WP}} + \frac{kA_N(T_N - T_P)}{\Delta y_{NP}} = 0 \quad (18)$$

For volume of control C:

$$-\varepsilon\sigma A_W(T_{BW}^4 - T_{amb}^4) + \frac{kA_E(T_p - T_E)}{\Delta X_{PE}} + \frac{kA_N(T_N - T_P)}{\Delta X_{NP}} - \frac{kA_S(T_P - T_{BS})}{\Delta y_{PS}} = 0 \quad (19)$$

For volumes of control inside block 9:

$$\frac{kA_N(T_N - T_P)}{\Delta y_{NP}} - \frac{kA_S(T_P - T_{BS})}{\Delta y_{PS}} + \frac{kA_E(T_E - T_P)}{\Delta X_{EP}} - \frac{kA_W(T_P - T_W)}{\Delta X_{WP}} = 0 \quad (20)$$

For volumes of control inside block 10:

$$\frac{kA_N(T_N - T_P)}{\Delta y_{NP}} - \frac{kA_S(T_P - T_{BS})}{\Delta y_{P,BS}} - \frac{kA_E(T_P - T_E)}{\Delta X_{EP}} + \frac{kA_W(T_P - T_W)}{\Delta X_{WP}} = 0 \quad (21)$$

For volume of control D:

$$-\varepsilon\sigma A_E(T_{BE}^4 - T_{amb}^4) - \frac{kA_S(T_P - T_{BS})}{\Delta y_{P,BS}} + \frac{kA_W(T_W - T_P)}{\Delta X_{WP}} + \frac{kA_N(T_P - T_N)}{\Delta y_{PN}} = 0 \quad (22)$$

3.2.3. Solution of equations

Discrete equations related to each control volume establish a system of equations. In this case, tri-diagonal matrix algorithm named as TDMA is the method adopted to solve this system of equation.

TDMA is a direct method for one dimensional situation that can be applied iteratively, in a line-by-line fashion, to solve multi-dimensional problems as per Malalasekera (1995).

3.3 Grid accuracy criterion

In order to avoid excessive computational time , a brief evaluation to find an optimized grid size was done. The criteria to choose the grid accuracy were the temperature distribution on the thermal doubler surface and the variation of maximum temperature.

The inputs for this evaluation are presented in Tab.1 for a thermal doubler with 0.1 m on vertical and horizontal directions.

This evaluation indicated that a uniform grid composed by 448 volumes of control presents a good mapping of the areas near to the top of doubler where heat flux is located, on the bottom surface and near to the West and East boarders. Additionally, the accuracy obtained by the usage of non-uniform grid near to boundaries is negligible (lower than 1°C).

3.4. Convergence criterion

The maximum temperature difference identified for each node between two successive iterations is the convergence criterion. In order to avoid unnecessary computational time and ensure a reliable equation system solution, a brief evaluation to find an optimized convergence criterion was done observing the maximum temperature of doubler. It was done considering the uniform grid chosen above.

From this sensibility analysis it was decided to stop the successive iterations when maximum temperature difference reaches 0.001 °C, once this criterion allow consistent mathematical results for the dimensional and temperature envelopes of inputs.

3.5. Sensibility analysis

The dimensional sensibility analysis was performed with a carbon composite and with aluminum alloy thermal doublers . The comparison criteria to study the correlation B/A was the maximum temperature. Range of B/A was changed from 0.025 to 2 for thermal doublers with height (B dimension) between 0.05m to 0.2m.

3.5.1 Inputs

The inputs for the sensibility analysis are listed on the Tab.1.

Thermal emissivity and thermal conductivity data for carbon composite were obtained, respectively, from Incropera (1998) and Enertron Catalog. For aluminum thermal doubler alloy, the thermal emissivity and conductivity properties were gathered from Kakaç (1985).

Table 1. Inputs for carbon composite doubler

Inputs	Carbon Composite	Aluminum Alloy
ε: Thermal emissivity	0.7	0.3
k: Thermal Conductivity	550 W/mK	200 W/mK
Heat Flow	10 kW/m²	10 kW/m²
Dimension X of Heat Flow	0.1m	0.1m
Thickness	0.01m	0.01m
Ambient Temperature	-50 °C	-50 °C

3.5.2 Results

The effect of B/A relation in the maximum temperature on carbon composite and on aluminum alloy thermal doublers, are presented, in this order, in Fig.4 and Fig.5.

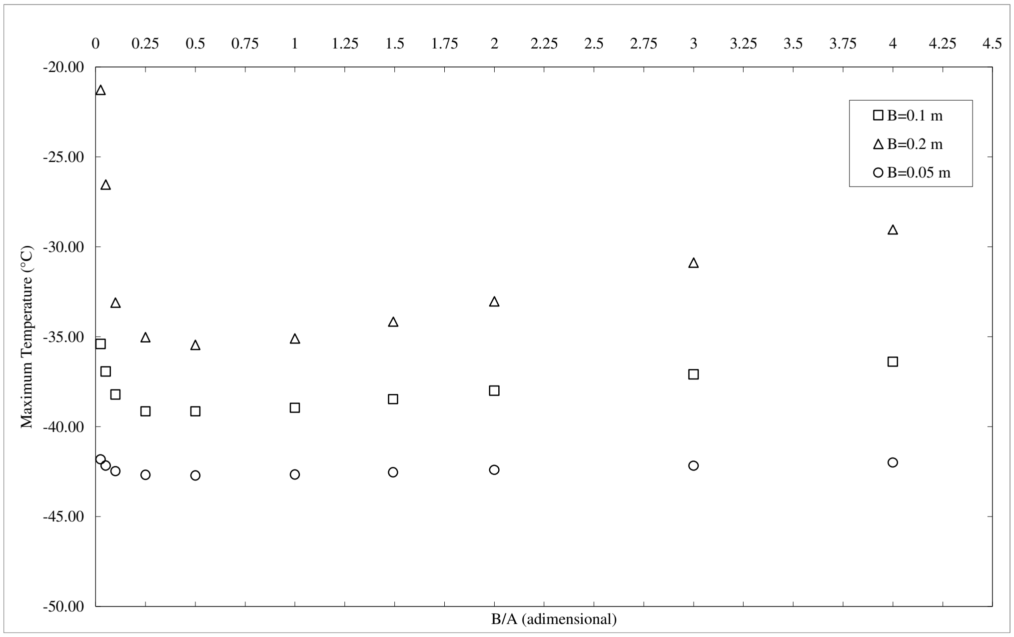

Figure 4. Maximum temperature for a carbon composite thermal doubler in function of B/A

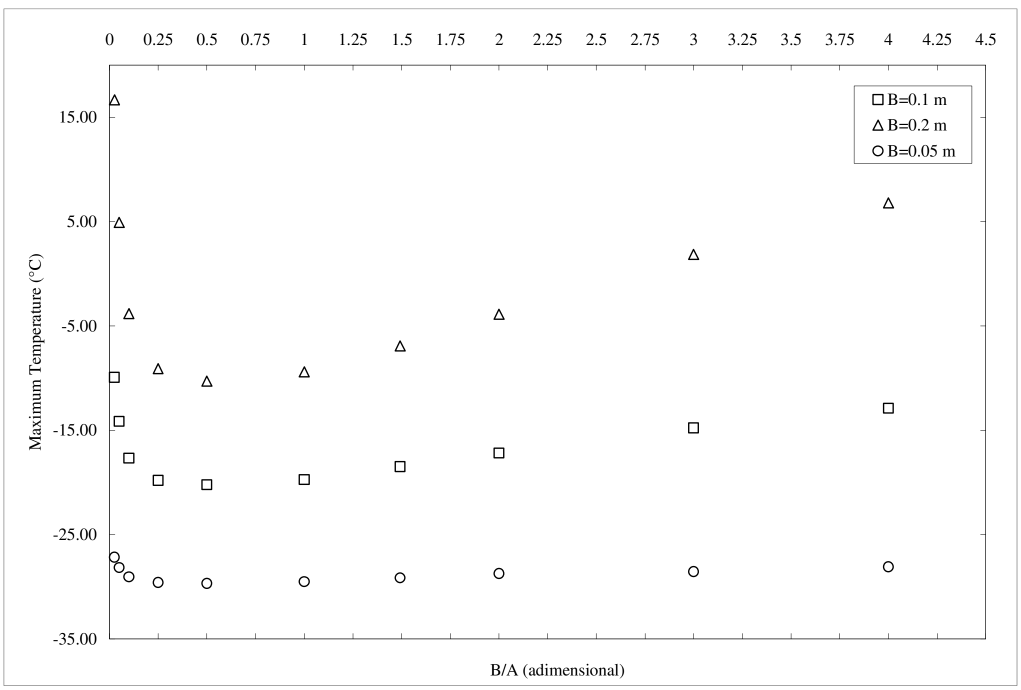

Figure 5. Maximum temperature for an aluminum alloy thermal doubler in function of B/A

Figure 4 and Fig.5 clearly shows that maximum temperature decreases until B/A equal to 0.25. It means that the reduction of dimension A reduces the conductive heat transfer resistance on horizontal direction and the heat transfer capabilities through the surface are improved even thought that this area was reduced.

In the B/A range between 0.25 and 1, it is noticed no significant changes on the maximum temperature value even with the reduction of heat conduction resistance on horizontal direction that limits the superficial diffusion capabilities of both doublers.

From B/A greater than 1, the reduction of dimension A is not beneficial because the negative effects of smaller superficial area overcome the positive effects of conductive heat transfer resistance reduction. Thus, the maximum temperature on thermal doublers starts to increase significantly.

As expected, the maximum temperatures are lower for carbon composite doubler because its heat transfer coefficient is greater than aluminum alloy.

The temperature distribution for carbon composite doubler is presented for the three regions of B/A in Fig.6, Fig.7 and Fig.8.

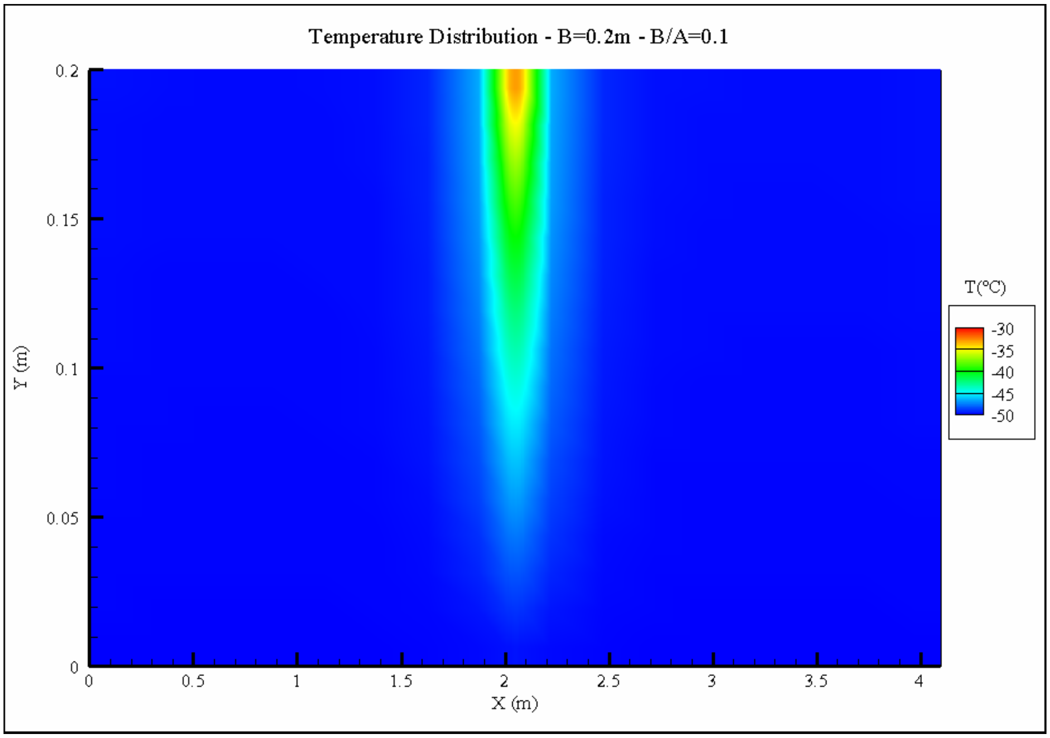

Figure 6. Temperature distribution for a carbon composite thermal doubler with B=0.2m and A/B=0.1

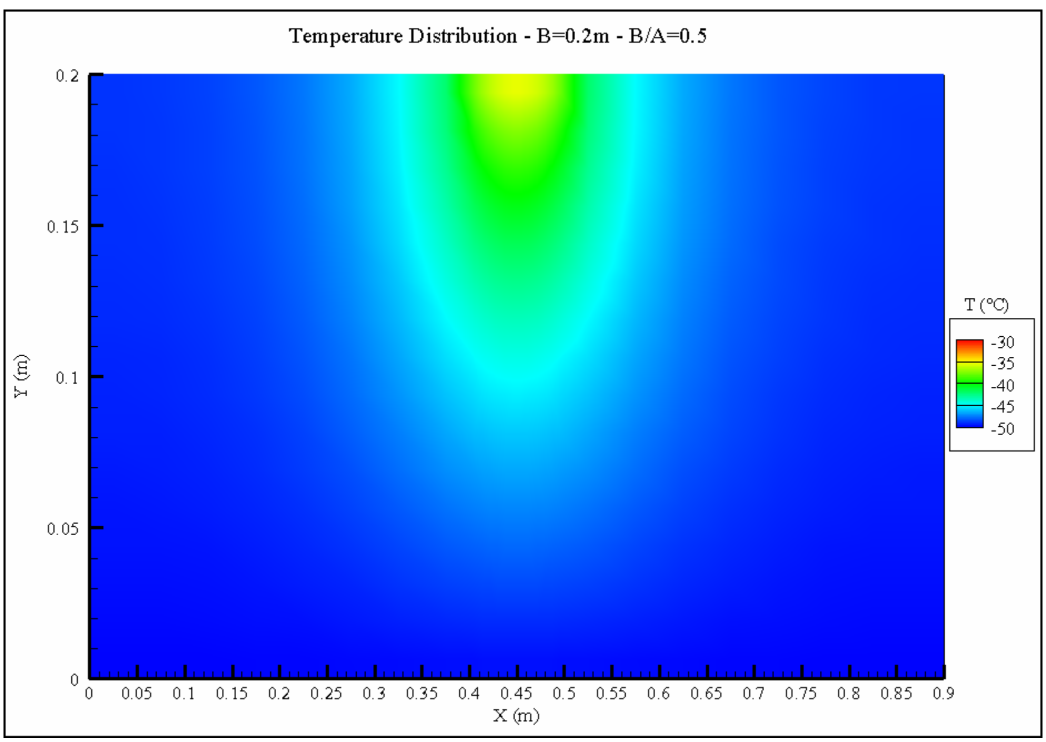

Figure 7. Temperature distribution for a carbon composite thermal doubler with B=0.2m and A/B=0.5

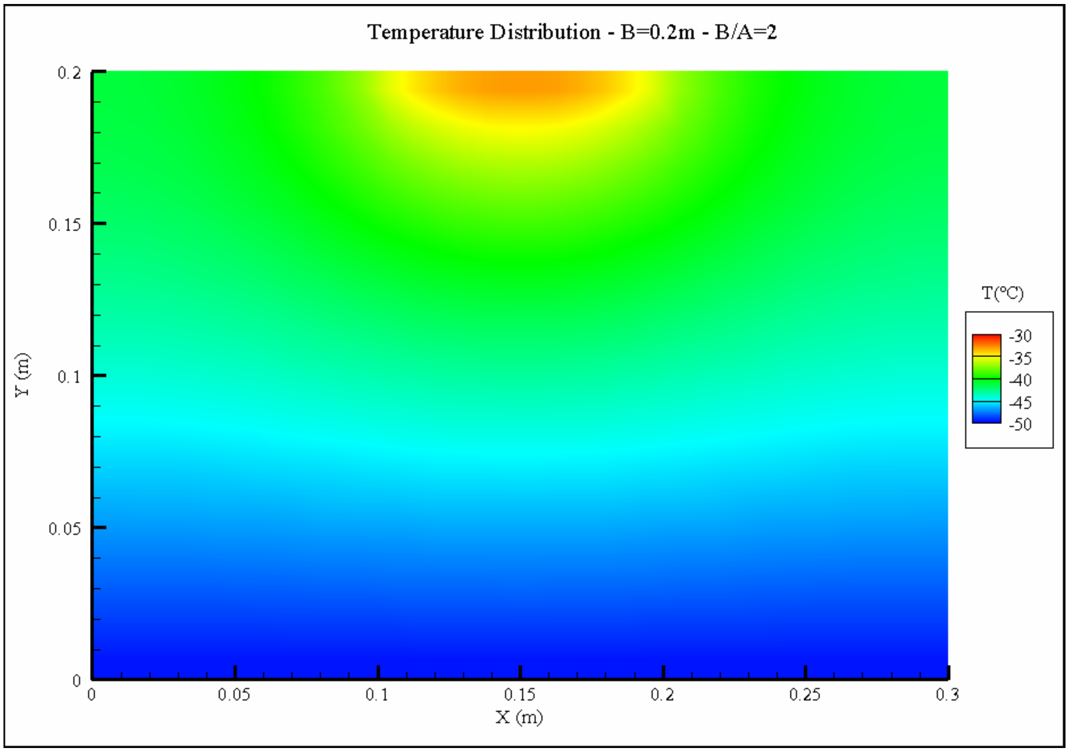

Figure 8. Temperature distribution for a carbon composite thermal doubler with B=0.2m and A/B=2

The greater temperature gradient in vertical direction verified in Fig. 6 and Fig. 8 illustrate the reduction of heat flow through the horizontal surface in comparison with Fig.7.

3.5.3 Conclusions

The results provided by this mathematical model have been physically consistent with conduction heat transfer theory and the numerical results are reasonable. It meets the engineering needs for starting the preliminary studies of cooling design.

The sensibility analysis has presented that there is a range where the correlation between doubler height (B) and horizontal (A) dimensions increase the heat transfer capabilities of thermal doubler. Out of this B/A range, the relation between heat transfer capability versus doubler weight is neither technically nor economically interesting.

Therefore, it is recommended to start the preliminary studies of a carbon composite or aluminum alloy thermal doublers adopting B/A relationship between 0.25 and 1. Additionally, carbon composites are preferable in relation to aluminum alloy due to smaller density.

4. REFERENCES

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