# APPLICATIONS OF COMSOL MULTIPHYSICS SOFTWARE TO HEAT TRANSFER PROCESSES

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Abstract:

This thesis used the study of Heat Transfer and COMSOL Multiphysics software as a reference which was made for the purpose of future education in engineering field. The main objective is to apply the COMSOL Multiphysics software into heat transfer processes. It consisted of a general view of three mechanisms of heat transfer: conduction, convection and radiation, which were presented in this thesis. It presented two methods of the performance to solve the three basic heat transfer problems. A simulation of radiator’s heat transfer process was performed by COMSOL Multiphysics in order to calculate the heat transfer rate. The final results shown that by reducing the thickness of radiator, it can increase the heat transfer rate. The author concluded that by reducing the thickness of radiator does not only increase the heat transfer rate but also save costs from material expenses.

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## LIST OF SYMBOLS

| | |
|---|---|
| $A$ | Area |
| $\alpha$ | Absorptivity |
| $c$ | Specific Heat at constant pressure |
| $E$ | Energy |
| $E$ | Emissive power |
| $E_b$ | Balckbody emissive power |
| $X,Y$ | Force |
| $G$ | Irradiation |
| $h$ | Heat transfer conefficient |
| $J$ | Radiosity |
| $k$ | Thermal conductivity |
| $L$ | Length |
| $p$ | Pressure |
| $q$ | Heat transfer rate |
| $q''$ | Heat flux |
| $\dot{q}$ | Heat generated per unit volume |
| $Q$ | Heat |
| $u, v, w$ | Velocity |
| $\varepsilon$ | emissivity |
| $\mu$ | Dynamic viscosity |
| $\rho$ | Density |
| $\rho$ | Reflectivity |
| $\sigma$ | Stefan-Boltzmann |
| $t$ | Time |
| $\tau$ | Transmissivity |
| $\tau_{yx}$ | Shear stress |
| $T$ | Temperature |

# 1 INTRODUCTION

## 1.1 Background

Since 1970s, the energy crisis has been listed in the five most essential worldwide problems. And the other four problems are respectively people, food, environment, and resource [1]. In this situation, energy saving becomes more important than ever. People are encouraged to contribute on sustainable development in daily life.

As a common heater, radiator is used for heating the room. It heats the environment by thermal energy, which is transferred from other forms of energy. A process of heat transfer exists when the radiator heats a room. The analysis on this process can be used for fully utilizing the energy. And the process is also taken as one of main purposes of studying heat transfer. [2]

Heat transfer has been widely used nowadays. Therefore, it is important for an engineer to have related knowledge on heat transfer. At the same time, following with the boom of the computer technology, certain types of Computer Software have been introduced for the purpose of analyzing heat transfer efficiently. Comsol Multiphysics software is one of them, which has been taken as a helpful tool for making analysis on the processes of heat transfer. In this thesis, the author introduces Comsol Multiphysics software and analyzes heat transfer processes.

## 1.2 Purpose

There are mainly two purposes of this thesis. The first one is to give implications to future engineering students. The author introduces about heat transfer and ways of using Comsol Multiphysics software to solve some problems. By doing so, this study is supposed to act as a foundation of further researches with the same subject.  The second purpose is to put the knowledge into practice. The author applies the Comsol Multiphysics software to simulate the radiator's heat transfer process so that the radiators' heat transfer rate can be calculated. Based on the analysis of the process, the author makes descriptions on the ways of improving radiator's heat effect.

## 1.3 Thesis Outline

*Theoretical chapter.* In this chapter, the author firstly introduces about definition of heat transfer. Then, it follows with descriptions about three basic transfer models: conduction, convection, and radiation. Meanwhile, there is a further discussion on the three models. Afterwards, the author gives an introduction about radiator, which is taken as an example of saving energy from heat transfer process. The principle of work and the type of radiator are mainly presented. Comes up with the last part of the theoretical review, it refers to the Comsol Multiphysicshs software. This part mentions about the software's historical development, functions and some other related characteristics.

The other two chapters of the thesis are *Method* and *Results*, which are two most essential parts of the thesis. In the first part of the Method chapter, the author chooses three basic heat transfer problems, which relates to three heat transfer models, and then solves them by theoretical method and Comsol Multiphysics software. In the second part, the author establishes a model simulation of a room, which installed a radiator. According to the definition of conduction, convection, and radiation, it is proved that the process of radiator's heat transfer contains all the three heat transfer models. Based on this knowledge, the author establishes a model with the help of Comsol Multiphysic software. The heat transfer rate of the radiator is supposed to be calculated according to the simulated room's temperature distribution. Finally, the results of the three basic heat transfer problems and heat transfer rate of radiator are stated in the Results chapter.

*Conclusion* is the last part of the thesis. In this part, the author compares the results of three problems obtained by theoretical method and Comsol Multiphysic software. A conclusion about the main factors of affecting the heat transfer process of a radiator is stated. Furthermore, there is a conclusion about the simulation results, which is obtained from model simulation.

# 2 OBJECTIVES

There are five main objectives in total, which have been stated as followings:

1. To offer a clearly introduction about three mechanisms of heat transfer:
    - Conduction
    - Convection
    - Radiation
2. To provide a general introduction to Comsol Multiphysics software
3. To solve three heat transfer problems with theoretical method and Comsol model method
4. To simulate the heat transfer processes between room and a radiator by using Comsol Multiphysics software.
5. To compute how much heat energy has been transferred from radiator.

# 3 LITERATURE SURVEY

## 3.1 Overview of Heat Transfer

Temperature is a common phenomenon in nature. And it was used to describe the hot and cold. From the perspective of micro-physical, the temperature stands for the intensity of molecular motion [3]. According to Holman [4, p1], energy transfer happens while temperature difference exists between material bodies. Heat transfer is such a science to be used for estimating the energy transfer.

When the temperature difference exists between material bodies, heat is always transferred from the hotter object to the colder one [2]. In other worlds, heat never goes from a colder object to a warmer object. The transfer of the heat can be discovered from everywhere in people’s daily life. For instance, the temperature of hot water starts to drop if putting an ice into the cup. This is because that the temperature of the water is higher than the ice so that heat is transferred from the water to the ice.

Heat transfer has been applied widely in various fields, there are mainly three research fields can be generated. These three aspects are [2, p2]:

1) How to increase the hate transfer rate.
2) How to decrease the hate transfer rate.
3) How to keep the temperature in certain range.

Heat transfer has three basic transfer models: conduction, convection and radiation. Regards to the study of heat transfer; it is divided into these three parts in this study as well. Accordingly, these three parts are introduced here one by one in detail.

### 3.1.1 Conduction Heat Transfer

Conduction is a process of heat transfer generated by molecular vibration within an object. The object has no motion of the material during the heat transfer process. The example below well explained about conduction heat transfer. [5]

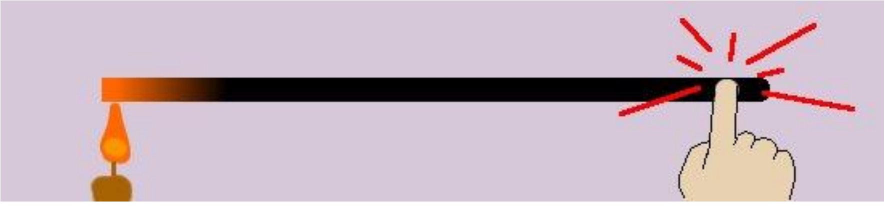


*Figure 1. Conduction heat transfer [6]*

As Figure 1, there is a metal stick. Using a candle to heat the left side of the stick for a while, then the right side of the stick will be found to be hot as well. It is because the energy has been transferred from the left side of the stick to the right side. And this kind of heat transfer is conduction.

#### *3.1.1.1 Conduction rate equation*

After knowing a subject's conduction is the heat transfer from one end to the other end, it is important for calculating about the heat transfer rate. Based on the experiment experiences, for the one dimension conduction heat transfer in a plane wall, the amount of heat energy being transferred per unit time is proportional to the normal temperature gradient $\frac{dT}{dx}$ and the cross-sectional area $A$ [7, p4], this can be expressed as:

$$q = -kA\frac{dT}{dx} \tag{1}$$

Where

$q$ is the heat-transfer rate, W

$A$ is cross-sectional area, $\mathrm{m}^2$

$k$ is the thermal conductivity of the material, W/(m.K)

$dT/dx$ is the temperature gradient

The Equation (1) is the formula of calculation of conduction heat transfer rate; it is also known as *Fourier's law of heat conduction*. The minus sign means heat transferred in the direction of decreasing temperature. If the heat transfer rate $q$ divided by the cross-sectional area $A$, the equation (1) can be derived as:

$$q'' = -k\frac{dT}{dx} \tag{2}$$

Where， $q''$ called conduction *heat flux*. The heat flux was derived from the Fourier's law of heat conduction; it can be described as the heat transfer rate through unit cross-sectional area.

The amount of the thermal conductivity $k$ indicates the substance's ability of transferring heat. If it is a big amount, it means the substance has high level of ability on heat transfer. The number of the thermal conductivity depends on the material; of course, it is also affected by the temperature outside. In the last part of the thesis, the heat transfer situation is observed by setting different thermal conductivities when simulating the heat transfer processes between room and radiator. [2]

### 3.1.1.2 Partial Differential Equation of Heat Conduction

Refers to the research on conduction, one of the most important purposes is to know how the temperature is distributing in the medium. Once the distribution situation of the temperature is known, the heat transfer rater can be calculated.

To derive a mathematical formulation of temperature distribution, both the law of the conservation of energy and the Fourier’s law should be used. On the basis of conservation of energy, the balance of heat energy for a medium expressed as [2, p41]

***[Energy conducted from outside of the medium] + [Heat generated within medium] = [Energy conducted to outside of the medium] + [Change in internal energy within medium]***

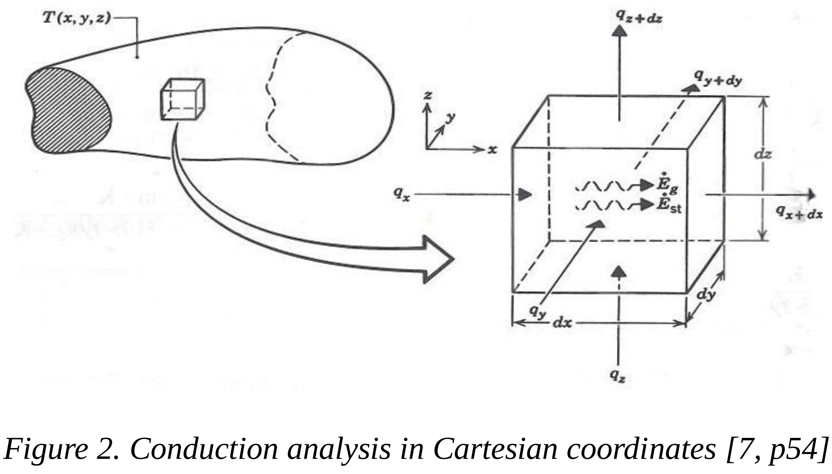


*Figure 2. Conduction analysis in Cartesian coordinates [7, p54]*

Figure 2 shows the heat-conduction energy balance in a Cartesian coordinates.

Based on the heat-conduction energy balance, the following equation was derived [7, p56]:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c\frac{\partial T}{\partial_t} \tag{3}$$

Where $\rho$ is density, kg/m$^3$

$c$ is the specific heat of material, $^J/_{kg.K}$

$\dot{q}$ is the Heat generated per unit volume, W/m$^3$

Equation (3) is called *differential equation of heat conduction*; it is also called *heat diffusion equation.* This equation describes the process of the general conduction heat transfer in mathematical method. When applying the equation to solve problems, the equation (3) will be simplified in accordance with the requirement of question and boundary conditions. Three common boundary conditions shows as following: [7]

a) Constant surface temperature:

$$T(0,t) = Ts$$

b) Constant surface heat flux:

$$-k\frac{\partial T}{\partial x}\Big|_{x=0} = q_s''$$

c) Convection surface condition:

$$-k\frac{\partial T}{\partial x}_{x=0} = h\,[(T_\infty - T(0,t)]$$

The heat equation (3) was expressed in a Cartesian coordinates. For cylindrical coordinates and spherical coordinates, the heat conduction energy balance is shown in Figure 3 and Figure 4. The heat diffusion equation is expressed as equation (4) and (5). [7, pp58-59]

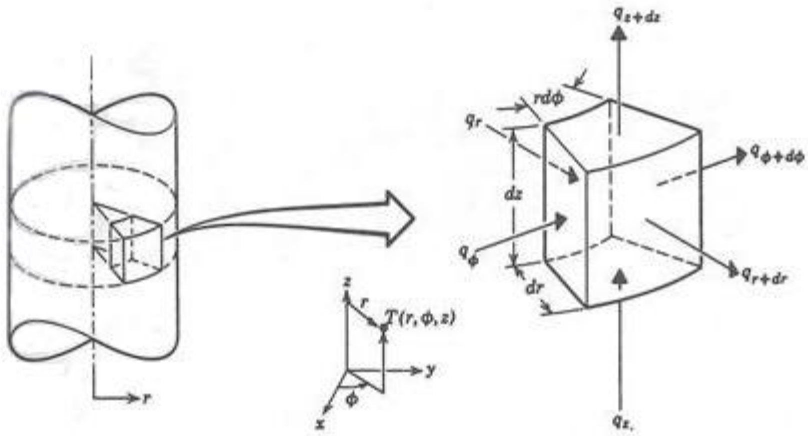


*Figure 3. Conduction analysis in Cylindrical coordinates [7, p54]*

**Cylindrical Coordinates**]:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \emptyset}\left(k\frac{\partial T}{\partial \emptyset}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c\frac{\partial T}{\partial_t} \qquad (4)$$

Where $\rho$ is density, kg/m$^3$

$c$ is the specific heat of material, $^J/_{kg.K}$

$\dot{q}$ is the energy generated per unit volume, W/m$^3$

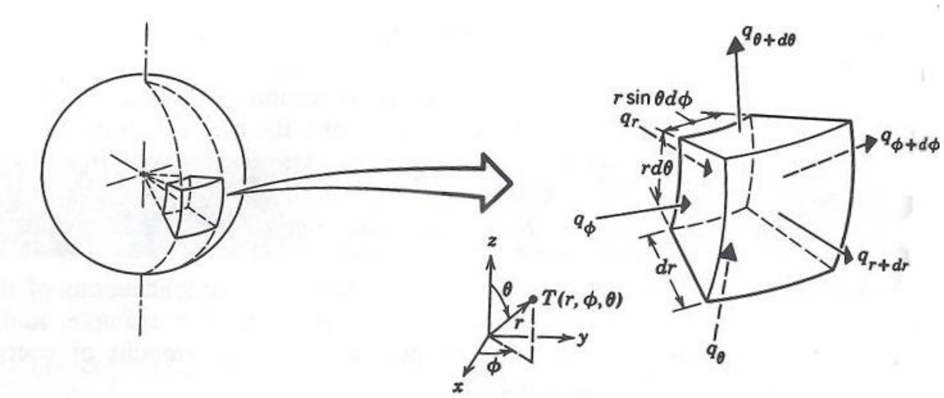


*Figure 4. Conduction analysis in Spherical coordinates [7, p54]*

**Spherical Coordinates**:

$$\frac{1}{r}\,\frac{\partial}{\partial r}\left(kr\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial}{\partial \emptyset}\left(k\frac{\partial T}{\partial \emptyset}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\dot{q}=\rho c\frac{\partial T}{\partial_t} \qquad (5)$$

Where $\rho$ is density, kg/$m^3$

$c$ is the specific heat of material, $^{J}/_{kg.K}$

$\dot{q}$ is the energy generated per unit volume, W/$m^3$

### 3.1.2 Convection Heat Transfer

Convection is the delivery of heat from a hot region to a cool region in a bulk, macroscopic movement of matter, which is opposed to the microscopic delivery of heat between atoms involved with conduction [8]. It means that convection must follow with conduction. In the system of convection heat transfer, the heat can be transferred within the fluid; it can be transferred between fluid and surface as well. The heat transfer between surface and fluid is called *convective heat transfer.* [2]

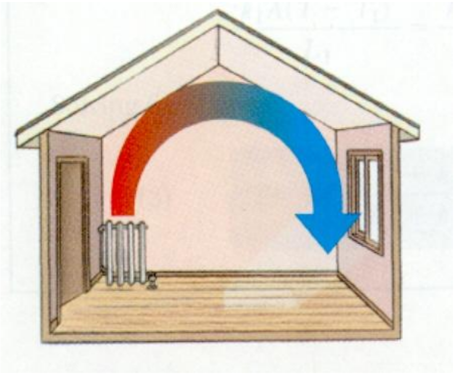


*Figure 5. Convection heat transfer [9]*

Figure 5 has shown heat convection in a room. The air around the radiator is heated up by the radiator and then moves to the cool region.

### *3.1.2.1 Newton's law of cooling*

The basic formula of calculating convective heat transfer rate is the Newton's law of cooling. The Newton's law of cooling can be used to express the overall effect of convection [2]:

$$q = hA\Delta T \tag{6}$$

Where

$q$ is heat-transfer rate;

$h$ is convection heat transfer coefficient, W/(m$^2$.k)

$A$ is area, m$^2$

$\triangle$T is temperature difference between fluid and surface, K

As formula (6) showing above, convection heat transfer coefficient is one of the most important parts of the formula. The main task of investigating the convection is to solve convection heat transfer coefficient. Once the heat transfer coefficient has been found, the heat transfer rate can be calculated. [2]

### *3.1.2.2 Overview of fluid mechanics.*

A fluid can be classified based on the physical characteristics of flow fields. Figure 6 shows one possible classification of flow.

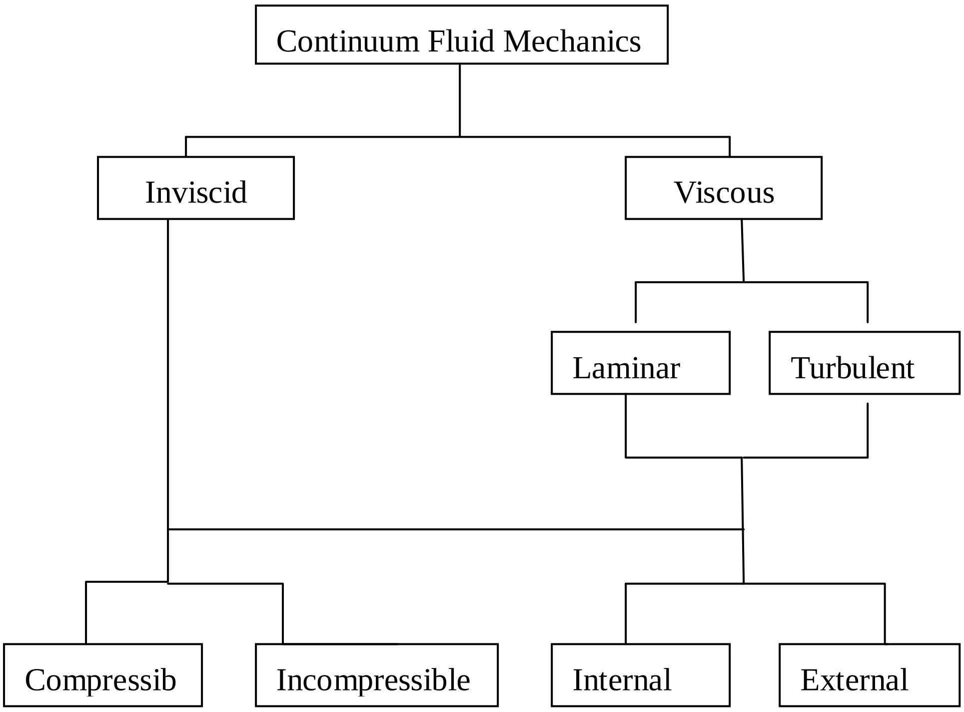


*Figure 6. Classification of continuum fluid mechanics [10]*

*Newtonian fluid* is defined as that the surface shear stress is directly proportional to rate of deformation, which is expressed as [10]:

$$\tau_{yx} = \mu \frac{\partial u}{\partial y} \tag{7}$$

Where $\tau_{yx}$ is shear stress

$\mu$ is the dynamic viscosity

$u$ is velocity

*Viscous flows and Inviscid flows* are both Newtonian fluid, the difference is that the viscosity of inviscid flows are neglected. Accordingly, the fluid viscosity is assumed to be zero. [10]

*Laminar and Turbulent flow* are classified based on the flow structure. The structure of laminar flow is characterized by smooth motion layers. Being different with laminar flow, the structure of the Turbulent flow is random. [10]

*Internal and External flow.* The main difference between them is if a flow is completely bounded by solid surface. [10]

*Compressible and Incompressible Flows* are termed on the basis of density variations. Incompressible flow is termed as the density variations are negligible. In contrast, if the flows in which variations in density are not negligible, it called compressible flows. [10]

#### ***3.1.2.3 Convection Transfer Equation***

#### **Convection boundary layer**

When a viscous Newtonian flow over a flat plate, the liquid velocity near the wall falls down quickly, and then a thin layer is formed on the surface of the plate. This layer is called boundary layer. Holman [4] also gave a clear concept that the boundary is described as the observation of viscosity phenomena of the area of flow which derives from the leading edge of the plate, both laminar and turbulent developed in this region. The Reynolds number, which is the ratio for inertia forces to viscous forces, is used for distinguish the laminar region and turbulent region in the boundary layer. The Reynolds number expressed as: [11] [4, pp216-217]

$$Re_x = U_\infty x / v \tag{7}$$

Where $\rho$ is the density of flow,

$U_\infty$ is free-stream velocity

$v = \mu/\rho$ is kinematic viscosity

$x$ is distance from leading edge

A laminar region occurs when $Re_x \leqslant 5 \times 10^5$.

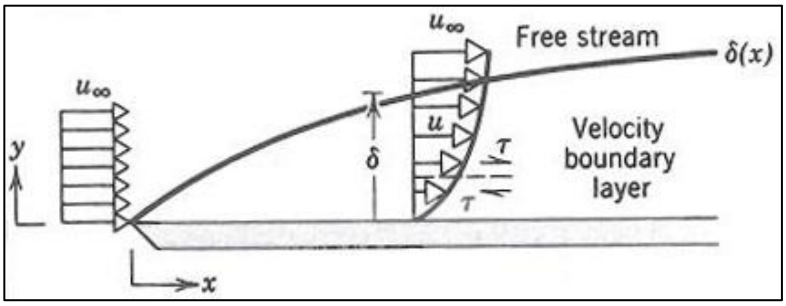


*Figure 7. Velocity boundary layer development on a flat plate [7, p318]*

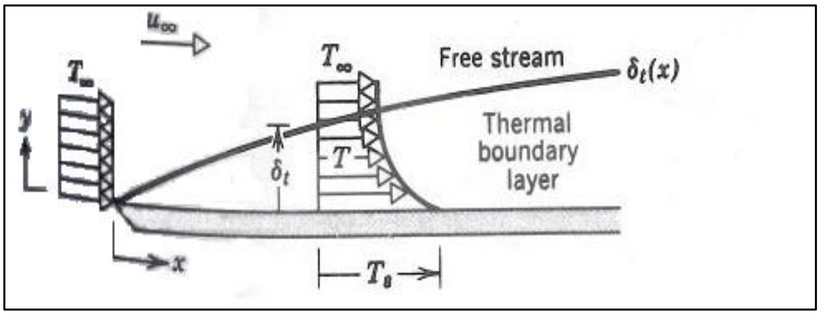


*Figure 8. Thermal boundary layer development on a flat plate [7, p319]*

Figure 7-8 shows the velocity and thermal boundary layer, respectively. As Yang & Tao [2] said that the heat transferred through this boundary layer. Based on these boundary layers, the convection equation is derived

To describe convective heat transfer problems with mathematical formulation, the Continuity Equation, Momentum Equation and Energy Equation should be applied. [2]

**Continuity Equation on boundary layer**

Conservation of mass is described as [10, p182]:

*[Net rate of mass flux out through the control surface]*

*+ [Rate of mass inside the control volume] = 0*

For mass conservation in the two-dimensional velocity, the mass conservation is expressed as [7, p327]:

$$\frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} = 0 \tag{8}$$

Where $\rho$ is density,

$u$ and $v$ are velocity.

The equation (8) is also called continuity equation.

**Momentum Equation on boundary layer**

Within the unit time, the momentum balance for a control volume is given by: [4. 12]

[Rate of change of momentum inside the control volume] + [Net rate of flux of momentum out through the control surface] = [Forces acting on the control volume]

The momentum equation in a two-dimensional velocity boundary layer is expressed as: [7, p331]

The x-momentum equation:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial p}{\partial x}+\frac{\partial}{\partial x}\left\{\mu\left[2\frac{\partial u}{\partial x}-\frac{2}{3}\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]\right\}+\frac{\partial}{\partial y}\left[\mu\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right)\right]+X \qquad (9)$$

The y-momentum equation:

(10)

Where, $X$ and $Y$ are the forces

$p$ is the pressure

Formula (9) and (10) are also called Navier-Stokes equations.

**Energy Equation on boundary layer**:

As same as the description of energy equation in conduction section, the energy equation for a two-dimensional boundary layer is [7, p331]:

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}\right)=\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\mu\vec{\emptyset}+\dot{q} \qquad (11)$$

Where, $\mu\vec{\emptyset}$ is viscous dissipation.

The formula (8)-(11) are the partial differential equations of convection heat transfer. It is difficult to solve the equations if considering all of the terms, the simplified equations can be derived by considering the boundary layer as *incompressible*, having *constant properties*, *negligible body forces* and without *energy generation*. [7, p341]

### *3.1.2.4 The convection coefficients*

According to Newton's Law of cooling, once the convection heat transfer coefficient is known, we can compute how much heat has been transferred between the flow and object. The convection coefficients is influenced by a number of factors during the process of the heat transfer, for instance, the density of the flow, the viscosity of the flow, the velocity of the flow and so on. The analysis of convection heat transfer equation is about to obtain a formula for convection heat transfer coefficient in different conditions. The formula below can be used for computing the convention heat transfer coefficient of a flow over plate plane. [2]

$$h = 0.332\frac{k}{x}(Re_x)^{1/2}(Pr)^{1/3} \qquad (12)$$

Where $Re_x$ is Reynolds Number,

$Pr = \frac{\upsilon\rho c_p}{k}$ Prandtl Number.

The equation (12) also can be written as:

$$\mathrm{Nu_x} = \frac{h_x x}{k} = 0.332(Re_x)^{1/2}(Pr)^{1/3} \qquad (13)$$

Where $Nu_x$ is called Nusselt Number

### 3.1.3 Radiation Heat Transfer

For conduction and convection heat transfer, the heat can only be transferred through a material medium. Whereas, the radiation heat transfer can exist in vacuum. Energy transfer through electromagnetic waves is called as radiation. And the thermal radiation is a radiation propagated as a result of a temperature. Finally, radiation heat transfer is defined as "heat transfer by the emission of electromagnetic waves which carry energy away from the emitting object. [13]" [2. 4]

#### *3.1.3.1 Properties of radiation*

A radiant energy transmitted can be reflected, absorbed and transmitted when it strikes a material surface. According to the Energy Balance Equation, the relationship of them can be expressed as: [4]

$$\alpha + \rho + \tau = 1 \tag{14}$$

where, $\alpha$ is absorptivity, $\rho$ is reflectivity and $\tau$ is transmissivity.

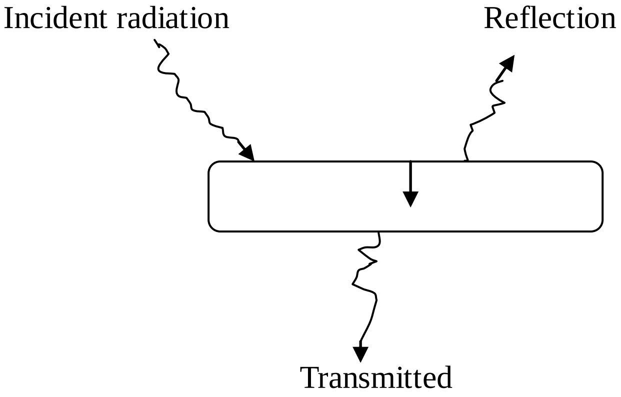


*Figure 9. Effects of incident radiation [4, p386]*

Figure 9 shows the effects of incident radiation. If a body absorbs total incident radiation, this body is called Blackbody. Therefore, the abosorptivity of blackbody is 1.

### *3.1.3.2 Stefan-Boltzmann law of thermal radiation*

A concept of the emissive power was given by Holman [4] as “the energy emitted by the body per unit area and per unit time”, it is marked with $E$. [4, p386]

The Stefan-Boltzmann law of thermal radiation describes a relationship between emissive power of a blackbody and temperature. It shows as:

$$E_b = \sigma T^4 \qquad (15)$$

Where $E_b$ is the energy radiated per unit time and per unit area.

σ is the *Stefan-Boltzmann constant* with value of $5.669 \times 10^{-8}\ W/m^2K^4$

$T$ is temperature, $K$

Equation (15) is called as the Stefan-Boltzmann law. Based on the law, it is known that a subject’s emissive power increases as soon as the subject’s temperate rises.

The blackbody is an ideal body. Thus, when under the scenario of the same temperature, the emissive power of the blackbody always has a stronger temperature degree than the actual body. The ratio of the emissive power between the real body and blackbody at the same temperature is called emissivity of the real body, which is [2, p365]:

$$\varepsilon = {}^{\mathrm{E}}/_{\mathrm{E_b}} \tag{16}$$

Then the emissive power of a real body can be expressed as:

$$\mathrm{E} = \varepsilon E_b = \varepsilon \sigma T^4 \tag{17}$$

The emissivity of a blackbody is 1.

### *3.1.3.3 Radiation Energy Exchange*

**Radiation Energy Exchange between blackbodies**

To calculate the energy exchange between two blackbodies with surfaces $A_m$ and $A_n$, the following expression would be applied:

$$Q_{1\text{-}2} = E_{bm} A_m F_{mn} - E_{bn} A_n F_{mn} \tag{18}$$

Where $F_{mn}$ is the fraction of energy leaving surface $m$ which reaches surfaces $n$.

**Radiation Energy Exchange between non-blackbodies**

Holman [4] has given definitions for two terms in order to calculate the radiation energy exchange: Irradiation $G$ and Radiosity $J$. Irradiation is “the total radiation incident upon a surface per unit time and per unit area [4, p410]” and Radiosity is “total radiation which leaves a surface per unit time and per unit area [4, p410]”. As a result, the radiosity on a surface can be calculated by the following formula, which has been mentioned by [4, p411]:

$$J = \varepsilon E_b + \rho G = \varepsilon\sigma T^4 + \rho G \tag{19}$$

Where $\varepsilon$ is emissivity

$E_b$ is the blackbody emissive power

$\rho$ is the reflectivity

$\sigma$ is the *Stefan-Boltzmann constant*

According to equation (18) and (19), an inferential reasoning formula (20) can be used for calculating the radiation energy loss of an object in a large room. [4, p418]

$$q = \sigma A_1 \varepsilon_1 (T_1^4 - T_2^4) \tag{20}$$

Where $A_1$ is the area of the object

$\varepsilon_1$ is the emissivity of the object

$T_1$ is the temperature of the object

$T_2$ is the temperature of the room.

## 3.2 Radiator

### 3.2.1 Working theory of radiator

A heat exchanger works as a specialized device of helping the heat to transfer from the hot fluid to the cold one. [14]. Heat exchanger not only exists in the aspect of engineering but also happens in people’s life. Working as a heat exchanger, the radiator can be used to increase the temperature of a room or a car etc. In this study, the author focuses on analyzing about how a heat exchanger can be used for rising a room’s temperature.

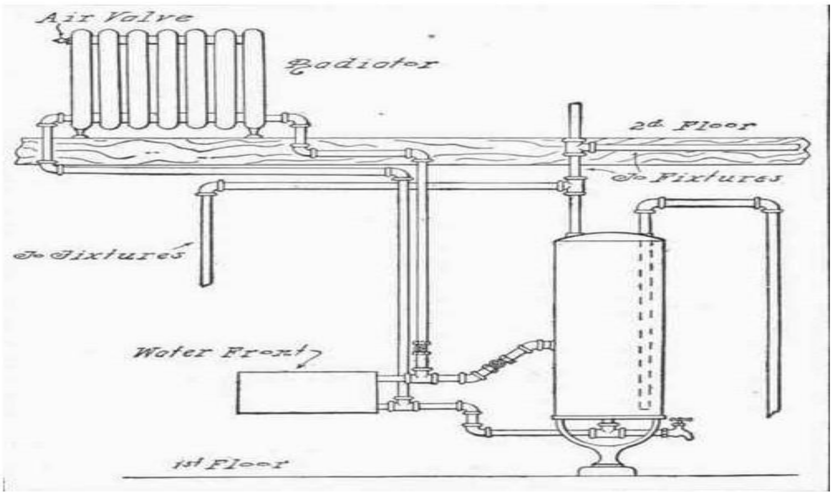


*Figure 10. Radiator heated from range boiler [15]*

The most common radiator nowadays is stream radiator. As Figure (10) shows, it describes about the working principle of the stream radiator. Firstly, the boiler produces stream or hot water, which will then be transferred through pipes to the radiators in a building. Finally, heat radiates from the radiator either in the way of radiation or convention, so that the temperature of the room rises. Within the whole process, the boiler works as a device, which transfers other forms of energy to thermal energy. [16] [17]

### 3.2.2 Classification of radiator

According to the differences on the raw material, the radiator is classified into the following types: [18]

- Cast iron radiator
- Stainless steels radiator
- Aluminum alloy radiator
- Copper/Aluminum Clad Materials radiator

## 3.3 COMSOL Multiphysics Software

Following with the major boost brought by computer technology, more and more computer software has been widely developed and used in the arena of engineering. The usage of the software can help engineers to solve problems efficiently. COMSOL Multiphysics is the software, by using which, engineer can not only make drawings but also do physical analysis.

### 3.3.1 History

The COMSOL Group was founded by Mr. Svante Littmarck and Mr. Farhad [19] in Sweden in 1986. It has now grown to United Kingdom, U.S.A, Finland and so on. Nowadays, The COMSOL Multiphysics software has been widespread used in various domains of science research and engineering calculation, for example, it was used in global numerical simulation. [19][20]

COMSOL Multiphysics is a finite element analysis, solver and Simulation software package for solving various physics and engineering applications. The first version of COMSOL Multiphysics software was published in 1998 by COMSOL group and it was named as Toolbox. At the beginning time, this software is only applied in the field of Structural Mechanics. “The COMSOL Multiphysics simulation environment facilitates all steps in the modeling process —defining your geometry, specifying your physics, meshing, solving and then post-processing your results [20]”.

### 3.3.2 Application areas

There are several application-specific modules in COMSOL Multiphysics. The most common applications are [19]:

- AC/DC Module
- Acoustics Module
- CAD Import Module
- Chemical Engineering Module
- Earth Science Module
- Heat Transfer Module
- Material Library

In this thesis, only Heat Transfer Module will be introduced and used in order to solve the relating problems of heat transfer.

### 3.3.3 Characteristics

The spread usage of COMSOL Multiphysics in various domains largely depends on its marked characteristics. These characteristics are [19]:

- It can be used to solve multi-physics problem
- The user can specify their own Partial Differential Equations
- Professional predefined modeling interfaces
- CAD models can be made directly
- CAD package can be added
- Exuberance of simulation capability

# 4 METHOD

Three basic problems concerning conduction heat transfer, convection heat transfer and radiator heat transfer were chosen from exercises of the book *Heat Transfer* [2] will be presented in the first part of this chapter. The author solves three problems with both theoretical method and COMSOL model method. For the theoretical method, some formulas, which presented in the literature survey chapter, are applied. In the second part, a heat transfer processes simulation between a radiator and a room are presented.

## 4.1 Heat Transfer Problems Analysis

### 4.1.1 Problems

PROBLEM 1:

The wall with area 12 $m^2$ on a side is constructed from brick. The wall has a thermal conductivity of 1.5 W/(m*K). Thickness of the wall is 260mm. The temperatures of 25 ℃ and -5 ℃ at the inner and outer surfaces of the wall were measured, respectively. What is the rate of heat loss through the wall?

PROBLEM 2:

As Figure 11 shows, it is a steady-state heat transfer process. Wall 1 having a thermal conductivity of 46.5 W/(m*K) connected with wall 2 having thermal conductivity of 1.16 W/(m*K). The temperature of surface 1 is 460℃. A flow, which closes to surface 2 of wall 2, has a temperature 300 ℃. The convection coefficient between wall 2 and flow is 5800 W/($m^2$*K). The thickness of wall 1 and wall 2 is 5mm and 0.5mm, respectively. What is the rate of heat loss from the surface of wall 2 per unit area?

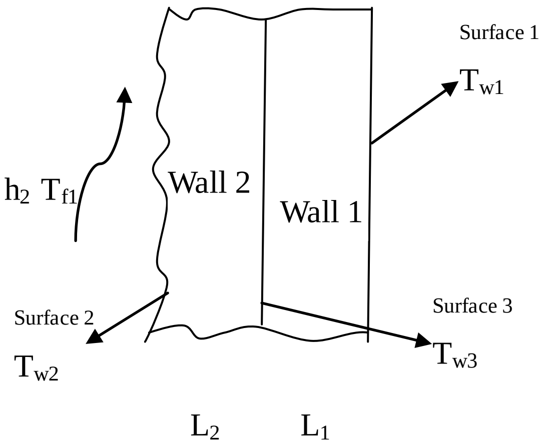


*Figure 11. Schematic plot of problem 2*

PROBLEM 3:

Aerospace is likely to be a vacuum space, where the temperature is 0K. Assume that there is a spacecraft flying in aerospace, the temperature is 25K, and the emissivity of the aircraft surface is 0.7, what is the heat loss of the surface per unit area?

### 4.1.2 Theoretical Method Solutions

To solve a heat transfer problem with theoretical method, the following steps will be applied by author [7]:

1) Known: State out what has been told in the problem.

2) Find: State out what need to be finding out.
3) Assumption: State all pertinent to simplify the question.
4) Analysis: Apply the heat transfer laws to the problem, substituting numerical values and get the results.

### 4.1.2.1 Problems 1

Known: Wall thickness $L$ = 260mm = 0.26m

Inner surfaces temperatures $T_0$ = 25 ℃ = 298 K

Outer surfaces temperatures $T_1$= -5 ℃ = 268 K

Area of the wall $A$ = 12 $m^2$

Thermal conductivity $k$ = 1.5 W/(m*K)

Find: Rate of the heat loss $q$

Assumptions: 1. Steady-State conduction conditions

2. One-dimensional conduction through the wall

3. Constant properties

Analysis: The schematic plot shows as figure 12. The Fourier's Law of heat conduction is applied to solve the problem. Using Equation (1):

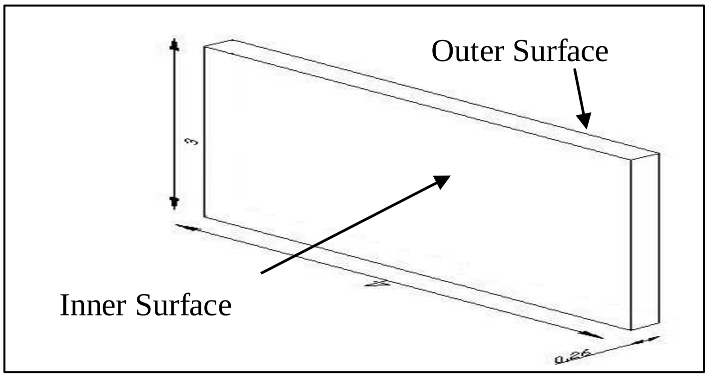


*Figure 12. Schematic plot of problem 1*

$$q = -kA\frac{dT}{dx} = -kA\frac{T_1 - T_0}{L}$$

$$= -1.5\, {}^{W}\!/_{mK} * 12\, m^2 * \frac{268K - 298K}{0.26m}$$

= 2077 W

#### *4.1.2.2 Problem 2*

Known: Plate thickness $L_1$ = 5mm = 0.005m, $L_2$ = 0.5mm=0.0005m

Flat surfaces temperatures $T_{w1}$= 460 ℃ = 733 K

Flow temperatures $T_{f1}$= 300 ℃ = 573 K

Unit area $A$ = 1 $m^2$

Thermal conductivity of plate 1: $k_1$ = 46.5 W/(m*K)

Thermal conductivity of plate 2: $k_2$= 1.16 W/(m*K)

Convection coefficient $h$ = 5800 W/($m^2$*K)

Find: Rate of the heat loss $q$

Assumptions: 1. Steady-State conditions

2. One-dimensional heat transfer

3. Constant properties

Analysis: This heat transfer process consists of conduction and convection heat transfer. The equation (1) Fourier's Law of heat conduction is applied to solve the conduction heat transfer through each wall. The equation (6) Newton's law of cooling is applied to solve convection heat transfer.

Conduction heat rate in surface 3:

$$q_3 = k_1 A \frac{T_{w3} - T_{w1}}{L1}$$

$$=> T_{w3} - T_{w1} = \frac{q_3 L_1}{k_1 A_1} \quad (21)$$

Conduction heat rate in surface 2:

$$q_2 = k_2 A \frac{T_{w2} - T_{w3}}{L2}$$

$$=> T_{w2} - T_{w3} = \frac{q_2 L_2}{k_2 A} \quad (22)$$

Convection heat transfer rate between surface 2 and flow

$$q_4 = hA(T_{f1} - T_{w3})$$

$$=> T_{f1} - T_{w3} = \frac{q_4}{hA} \quad (23)$$

Since it is a steady-state condition, then:

$$q_2 = q_3 = q_4 = q$$

To add equations (21), (22), (23) together:

$$=> T_{f1} - T_{w1} = \mathrm{q}(\frac{\mathrm{L_1}}{\mathrm{k_1}} + \frac{\mathrm{L_2}}{\mathrm{k_2}} + \frac{1}{\mathrm{h}}) \quad (24)$$

The final equation derived from equation (24) is:

$$q = \frac{T_{f1} - T_{w1}}{\frac{L_1}{k_1} + \frac{L_2}{k_2} + \frac{1}{h}} * A$$

$$= \frac{460\mathrm{K} - 300\mathrm{K}}{\frac{0.005\mathrm{m}}{46.5\mathrm{W/(m * K)}} + \frac{0.0005\mathrm{m}}{1.16\mathrm{W/(m * K)}} + \frac{1}{5800\mathrm{W/(m^2 * K)}}} * 1\mathrm{m}^2$$

= 225kW

#### *4.1.2.3 Problem 3*

Known: Temperature of spacecraft surface $T_1$= 250K

Temperature of space $T_2$= 0K

Emissivity of spacecraft surface $\varepsilon = 0.7$

Find: Rate of the heat loss *q*

Assumptions: 1. Temperature of spacecraft surface is uniform

2. Emissivity of spacecraft surface is uniform

Analysis: Since the spacecraft is flying in a large space, equation (20) is well applied to compute the heat loss:

$$q = \sigma A_1 \varepsilon_1 (T_1^4 - T_2^4)$$

$$= 5.669 \text{ x } 10^{-8} \text{ W/(m}^2\text{K}^4\text{)* 1 m}^2\text{*0.7 * (250K}^4 \text{ - 0K}^4\text{)}$$

$$= 155\text{W}$$

### 4.1.3 COMSOL Model Method

Using COMSOL Heat Transfer Module to simulate heat transfer process, the following steps can be followed:

a) Geometry modeling. According to the subject’s shape and the condition of the question, a model (1D, 2D, or 3D) is established in COMSOL

b) Physics settings. Physics menu contains two settings, which are subdomain settings and boundary settings. *Subdomain settings* is for setting each domain's material property, initial conditions etc. *Boundary settings* is for setting boundary conditions in two aspects. Firstly, it can set boundary conditions on the interface of different materials. Secondly, it can also set boundary conditions on the interface between material and the environment.

c) Solving. COMSOL Multiphysics's solver can be selected for dealing with different problems. Users can either select the proper solver according to their problem or use the default setting. Refers to this thesis, the author use the default setting to solve the three heat transfer problems

#### *4.1.3.1 Problem 1*

Before starting geometry modeling, some of the constants can be expressed by words in the "*Constants*" under the "*Options"* menu. The Table 1 below shows the known constants in the problem1.

*Table 1. Constants of problem 1*

| **Name** | **Expression** | **Description** |
|---|---|---|
| k_wall | *1.5[W/(m*K)]* | Thermal conductivity of wall |
| T_in | 298[K] | The temperature of inner surface |
| T_out | 268[K] | The temperature of outer surface |
| A | *12[m^2]* | Area of the wall |

**Geometry modeling:**

As the assumptions and analysis of the question were already made in previous part of theoretical method, based on these assumptions and analysis, the author establish a 2D model of *Steady-State Analysis* under *General Heat Transfer* in *Heat Transfer Moduel.*

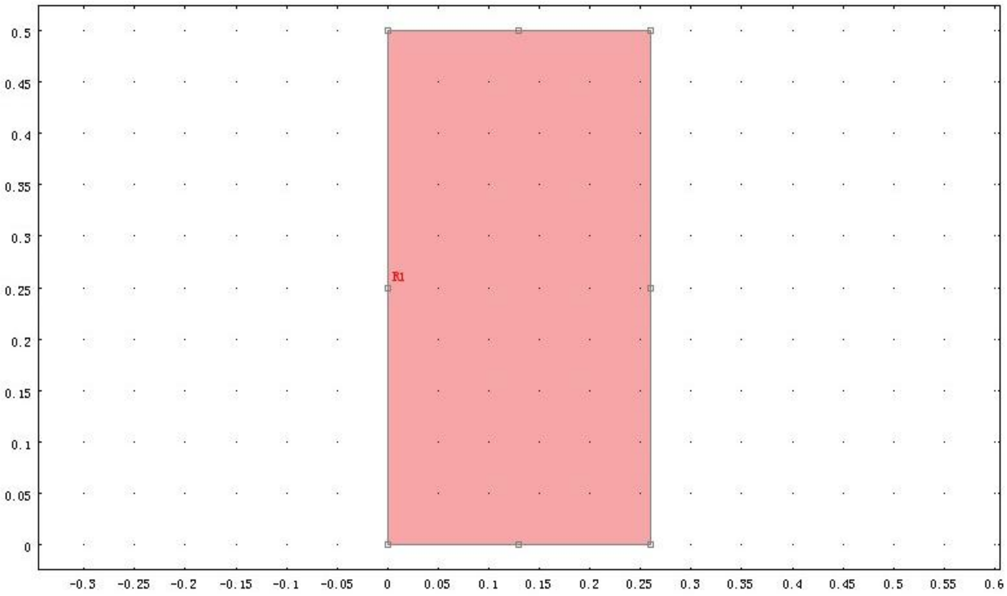


*Figure 13. Comsol model of problem 1*

Figure 13 shows above is the 2D's brick model. The width is 260mm and the height is 0.5mm.

**Subdomain Settings:**

*Subdomain Settings* is under the *Physics* menu. According to the known problem's condition, only the thermal conductivity of the wall needs to be inserted for the subdomain 1, which is the wall. All the others settings remain without any changes.

*Table 2. Subdomain Settings of problem 1.*

| **Subdomains** | **Description** | **Value/Expression** |
|---|---|---|
| 1 | Thermal conductivity | k_wall |

**Boundary Settings:**

Based on the assumptions made in the part of theoretical method, since the temperature is only transferred in one dimension, the boundary of the wall can be set according to Table 3.

*Table 3. Boundary Settings of problem 1*

| **Setting** | **Boundary 1** | **Boundary 4** | **Boundary 2, 3** |
|---|---|---|---|
| Boundary condition | Temperature | Temperature | Insulation / Symmetry |
| $T_0$ | T_in | T_out | |

**Solving:**

After completing all the settings mentioned above, it is the time to click *solve* button under the *Main toolbar* menu so that the problem 1 can be solved. Figure 14 shows the temperature distribution through the wall

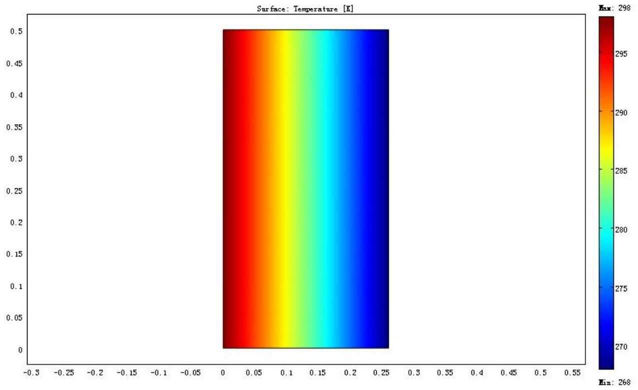


*Figure 14. Problem 1: Temperature distribution through the wall*

#### *4.1.3.1 Problem 2*

As same as problem1, in the first place, all related constants showing in Table 4 were set in Comsol software model.

*Table 4. Constants of problem 2*

| Name | Expression | Description |
|---|---|---|
| k_1 | *46.5 [W/(m*K)]* | Thermal conductivity of wall 1 |
| k_2 | *1.16 [W/(m*K)]* | Thermal conductivity of wall 2 |
| T_1 | *733 [K]* | Temperature of surface 1 |
| T_f | 573 [K] | Temperature of flow |
| H1 | *5800 [W/(m^2*K)]* | Convection heat transfer coefficient |

**Geometry modeling:**

Still based on the assumptions and analysis, which were mentioned before, a 2D model is applied to solve the question.

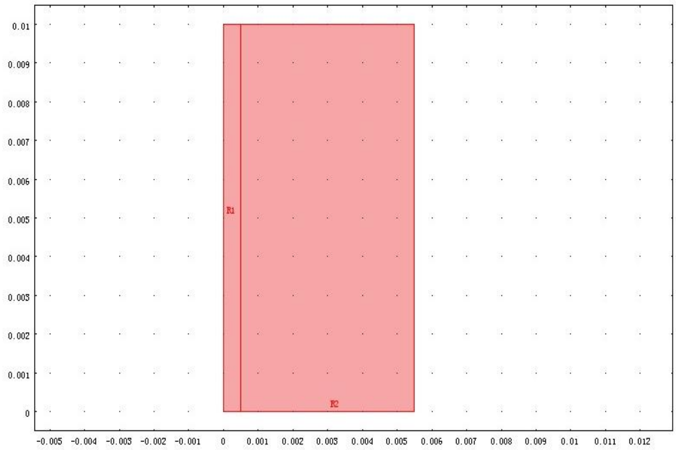


*Figure 15. Comsol model of problem 2*

Two rectangles represented the walls as show in Figure 15. Both of their height is 10mm. And the widths are respectively 0.5mm and 5mm.

**Subdomain Settings:**

Two subdomains appeared in this *Subdomains* list, for each domain, the settings are made in accordance with the Table 5.

*Table 5. Subdomain Settings of problem 2.*

| **Subdomains** | **Description** | **Value/Expression** |
|---|---|---|
| 1 | Thermal conductivity | k_2 |
| 2 | Thermal conductivity | k_1 |

**Boundary Settings:**

Problem 2 consists of two means of heat transfer. They are heat conduction and convection. Therefore, the boundary setting of problem 2 is more complicated comparing with the boundary setting of problem 1. The essential difference between their settings is in regard to surface 2. Table 6 is the Boundary Setting for all of the boundaries.

*Table 6. Boundary Settings of problem 2*

| **Setting** | **Boundary 1** | **Boundary 7** | **Boundary 4** | **Boundary 2, 3,5,6** |
|---|---|---|---|---|
| Boundary condition | Heat flux | Temperature | Continuity | Insulation/ Symmetry |
| T0 | | T_1 | | |
| T_inf | T_f | | | |
| h | H1 | | | |

**Solving:**

By clicking *solve* button on the main toolbar, a plot obtained shows the temperature distribution though wall 1 and wall 2 as Figure 16 shows below.

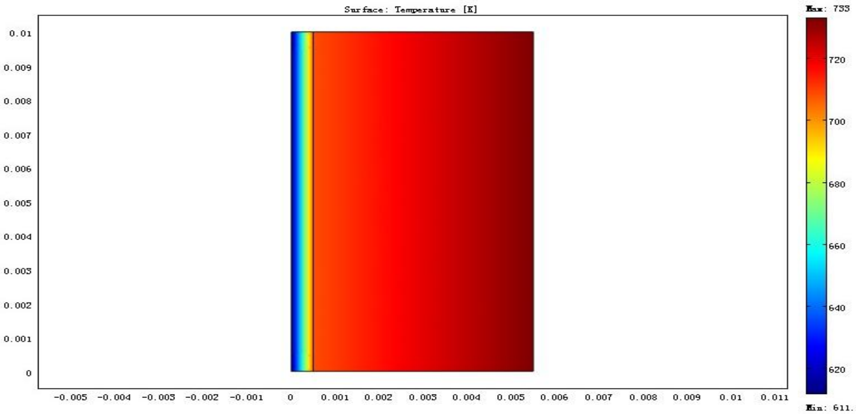


*Figure 16. Problem 2: Temperature distribution through the walls*

#### *4.1.3.1 Problem 3*

To solve the problem 3, all related constants were first set in Comsol software model. The constants are shows in Table 7.

*Table 7. Constants of problem 3*

| Name | Expression | Description |
|---|---|---|
| T_amb | 0[K] | The temperature of airspace |
| T_1 | 250[K] | The temperature of spacecraft |
| e1 | 0.7 | Emissivity |

**Geometry modeling:**

The spacecraft can be treated as a 3D box. Form this point of view. A 3D model (Figure 17) was applied to solve the problem 3.

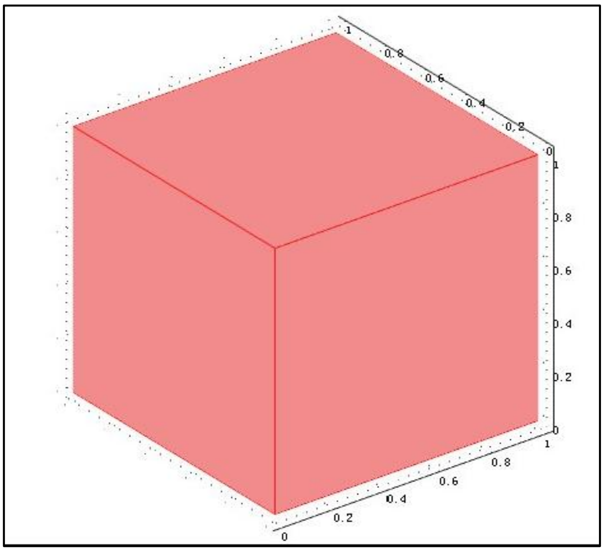


*Figure 17. Comsol model of problem 3*

**Subdomain Settings:**

For problem 3, only the initial value of temperature needs to be set on the *Init* page under *Subdomain Settings* dialog.

*Table 8. Subdomain Settings of problem 3.*

| **Subdomains** | **Initial value** | **Value/Expression** |
|---|---|---|
| 1 | T(t0) | 250 |

**Boundary Settings:**

All the boundaries of this model have the same boundary conditions. It is shown as Table 9:

*Table 9. Boundary Settings of problem 3*

| **Setting** | **Boundary 1,2,3,4,5,6** |
|---|---|
| Boundary condition | Temperature |
| $T_0$ | 250 |
| Radiation type | Surface-to-ambient |
| ε | 0.7 |
| T_amb | 0 |

**Solving:**

By clicking *solve* button on the main toolbar, a temperature distribution plot on the surface of the spacecraft is presented as Figure 18 shows.

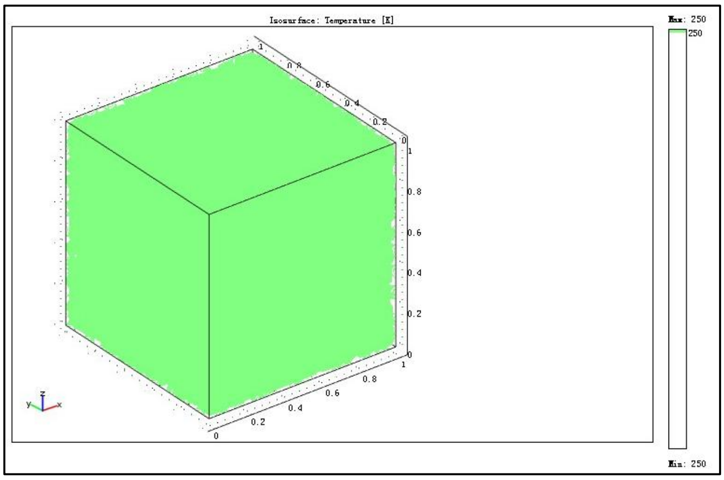


*Figure 18. Problem 3: Temperature distribution of spacecraft surface*

## 4.2 A Simulation of radiator heat transfer process

### 4.2.1 Model Analysis

#### *4.2.1.1 Heat transfer models between radiator and room*

First of all, assume that the heat transfer process of a radiator is a Steady-State condition. Then, according to the three ways of heat transfer, which were introduced in theoretical part, there are five processes existing in the heat transfer process within the room. These five processes are:

1) The heat is transferred from hot water to the radiator by free convection.
2) The heat is transferred through the radiator by conduction
3) Free convection from the radiator surface to the air
4) Free convection from the air to the wall
5) Radiation exchange between the outer surface of the radiator and the wall

#### *4.2.1.2 Property of the room*

Due to that this thesis focuses on the heat transfer between radiator and the room, the furniture are ignored. The room's length, width, and height are respectively 2m, 2m, 2.8m. The temperature in the room is 20 ° C. The material of the room's wall and ceiling is Gypsum. The floor is made of wood. Table 10 shows the emissivity of the wall and the ceiling.

*Table 10. Emissivities of material*

| Material | Emissivity ε |
|---|---|
| Gypsum | 0.90 |
| Wood | 0.91 |

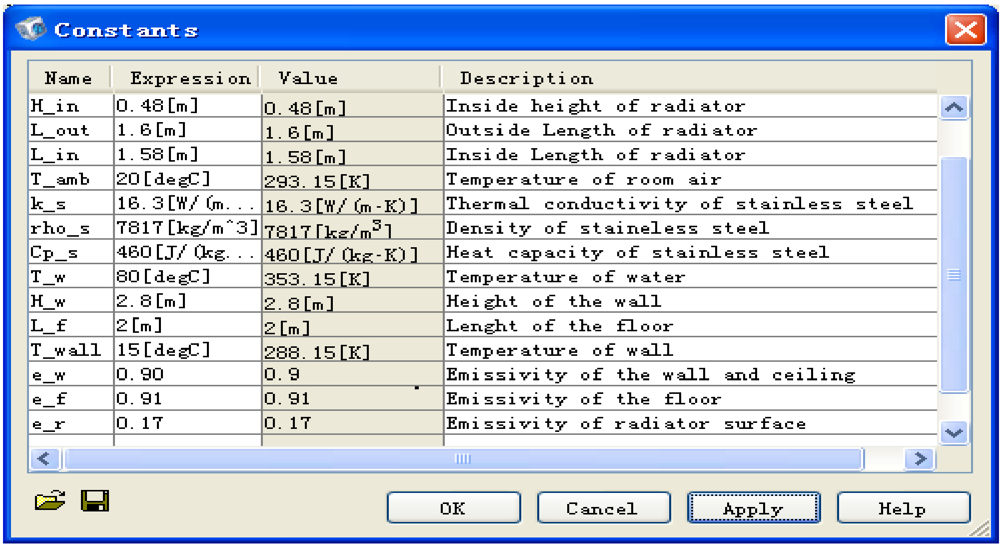
### ***4.2.1.3 Property of the radiator***

The size of the radiator is designed as: length 1.6m, width 0.05m, and height 0.5m. The thickness of the radiator is 0.01m. The water inside the radiator, is 80° C. As Table 11 shows, different materials have different properties at 20 ° C. In this chapter, only the stainless steels are used to present the heat transfer process:

*Table 11. Properties of material at 20 ℃*

| Material | Density $\rho$, (kg/m$^{3)}$ | Specific Heat at constant pressure $c_p$, (J/kg*K) | Thermal conductivity $k$, (W/m*K) | Emissivity ε |
|---|---|---|---|---|
| Stainless Steel | 7817 | 460 | 16.3 | 0.17 |
| Cast Iron | 7849 | 460 | 59 | 0.44 |
| Aluminum alloy | 2627 | 854 | 161 | 0.22 |
| Copper/Aluminum | 8666 | 410 | 83 | 0.78 |

## 4.2.2 Model Setting



| Name | Expression | Value | Description |
|---|---|---|---|
| H_in | 0.48[m] | 0.48[m] | Inside height of radiator |
| L_out | 1.6[m] | 1.6[m] | Outside Length of radiator |
| L_in | 1.58[m] | 1.58[m] | Inside Length of radiator |
| T_amb | 20[degC] | 293.15[K] | Temperature of room air |
| k_s | 16.3[W/(m... | 16.3[W/(m-K)] | Thermal conductivity of stainless steel |
| rho_s | 7817[kg/m^3] | 7817[kg/m$^3$] | Density of staineless steel |
| Cp_s | 460[J/(kg... | 460[J/(kg-K)] | Heat capacity of stainless steel |
| T_w | 80[degC] | 353.15[K] | Temperature of water |
| H_w | 2.8[m] | 2.8[m] | Height of the wall |
| L_f | 2[m] | 2[m] | Lenght of the floor |
| T_wall | 15[degC] | 288.15[K] | Temperature of wall |
| e_w | 0.90 | 0.9 | Emissivity of the wall and ceiling |
| e_f | 0.91 | 0.91 | Emissivity of the floor |
| e_r | 0.17 | 0.17 | Emissivity of radiator surface |

*Figure 19. Constants of radiator model*

Figure 19 states all relevant constants, which need for simulation of the radiator heat transfer model.

**Geometry modeling:**

Take the room and the radiator's size as a basis, 3D model of radiator and room is established in Heat Transfer Module. The 3D object is shown in figure 20.

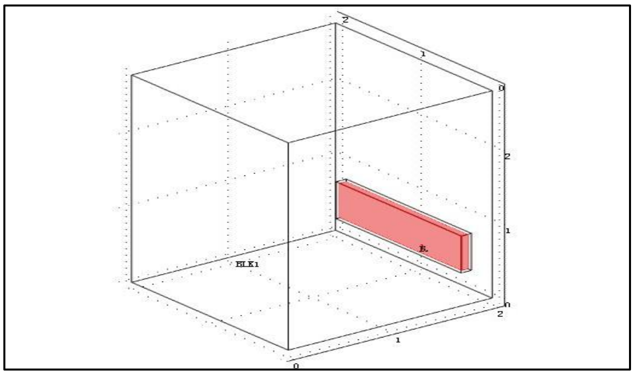


*Figure 20. Comsol model of radiator heat transfer process*

**Subdomain Settings:**

There are three domains in the model. These three domains are air, radiator, and hot water. The properties of air and water were loaded from library material in Comsol Multiphysics, The initial temperatures of air and water were set as *T_amb* and *T_w* in *Init* page, respectively. The Table 12 blow is about the Subdomains Setting of radiator subdomain:

*Table 12. Subdomain Settings of radiator model.*

| Subdomains | Description | Value/Expression |
|---|---|---|
| 2 | Thermal conductivity | k_s |
| | Density | rho_s |
| | Heat capacity | Cp_s |

**Boundary Settings:**

The heat transfer between radiator and room consists of three heat transfer models. For the convection, the heat transfer coefficient was loaded from the coefficient library. The loaded coefficient function will be modified according to the properties of the model. Table 13, 14 show all the boundary settings.

*Table 13. Boundary Settings of radiator model part1*

| **Setting** | **Boundary 1,2,5,18** | **Boundary 3** | **Boundary 4** | **Boundary 6,7,10,17** |
|---|---|---|---|---|
| Boundary condition | *Heat flux* | Heat flux | Heat flux | Heat source/sink |
| h | h_ave(T[1/K],Tinf_htgh[1/K],H_w[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],L_f[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],L_f[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],H_out[1/m])[W/(m^2*K)] |
| $T_{inf}$ | T_amb | T_amb | T_amb | T_amb |
| Radiation type | Surface-to-ambient | Surface-to-ambient | Surface-to-ambient | Surface-to-ambient |
| ε | e_w | e_f | e_w | e_r |
| $T_{amb}$ | T_wall | T_amb | T_amb | T_amb |

*Table 14. Boundary Settings of radiator model part2*

| **Setting** | **Boundary 8** | **Boundary 9** | **Boundary 11,12,15,16** | **Boundary 13** | **Boundary 14** |
|---|---|---|---|---|---|
| Boundary condition | Heat source/ sink | Heat source/sink | Heat source/sink | Heat source/sink | Heat source/sink |
| h | h_ave(T[1/K],Tinf_htgh[1/K],L_out[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],L_out[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],H_in[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],L_in[1/m])[W/(m^2*K)] | h_ave(T[1/K],Tinf_htgh[1/K],L_in[1/m])[W/(m^2*K)] |
| $T_{inf}$ | T_amb | T_amb | T_w | T_w | T_w |
| Radiation type | Surface-to-ambient | Surface-to-ambient | None | None | None |
| ε | e_r | e_r | | | |
| $T_{amb}$ | T_amb | T_amb | | | |

**Solving:**

Clicking the *solve* button, a default plot appeared as shows in Figure 21. It describes the temperature distribution inside the room.

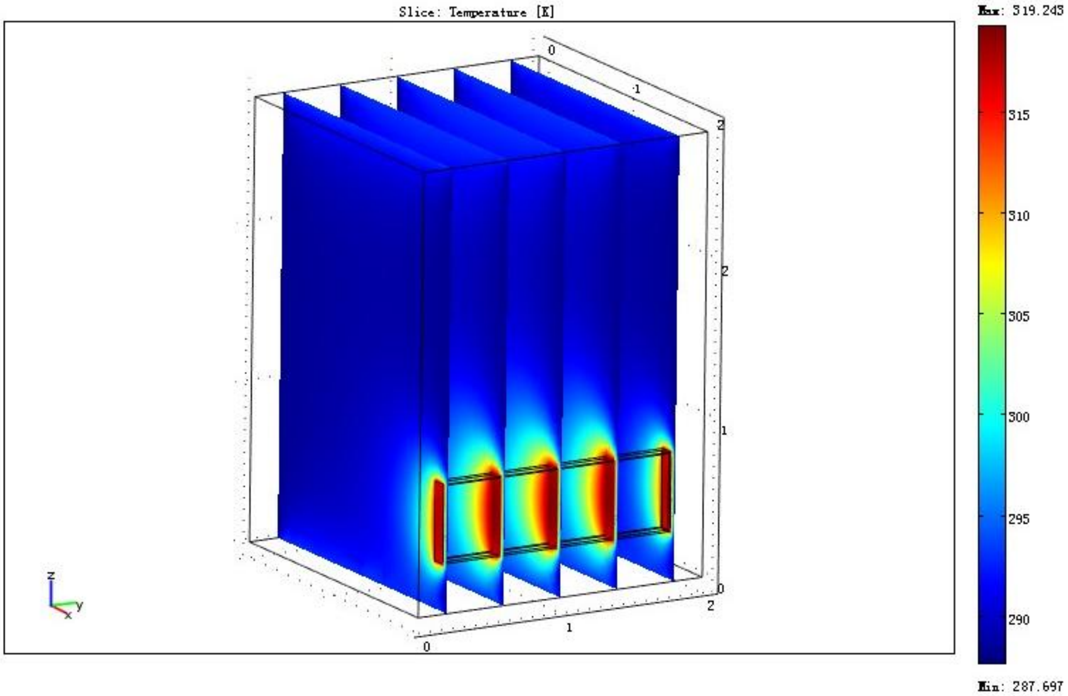


*Figure 21. Temperature distribution of radiator and room*

# 5 RESULTS

## 5.1 Three heat transfer problems

### 5.1.1 Theoretical Method results

Based on the analysis and assumptions of each questions, the results are showed in Table 15 after calculating by applying all relevant equations.

*Table 15 Results of three problems by using theoretical method.*

| **Problem** | **Results** |
|---|---|
| Problem 1 | 2077 W |
| Problem 2 | 225 kW |
| Problem 3 | 155 W |

### 5.1.2 Comsol model method results

The Comsol Multiphysics can postprocess any function by entering the corresponding expression. The expression can combine user-defined variables, application mode variables, and standard variables etc. [21] For this thesis, the function of *integration boundary* is applied to evaluate the heat transfer rate. By using this function, the results of these three questions were computed as shows in Table 16.

*Table 16. Results of three problems by using Comsol Multiphysics software.*

| **Problem** | **Results** |
|---|---|
| Problem 1 | 2076.923077 W |
| Problem 2 | 225043 W |
| Problem 3 | 155.039062 W |

## 5.2 Simulation of radiator heat transfer process

The heat rate through the surface of radiator was obtained by using *integration boundary* tool under *postprocessing* menu. According to the model of stainless steel radiator, three heat transfer processes (cast iron radiator, aluminum alloy radiator and copper/Aluminum radiator) are simulated. Table 17 below displays the heat rate of different radiator's material under the same condition.

*Table 17. Heat transfer rate of various material radiators.*

| **Material** | **Heat rate** |
|---|---|
| Stainless Steel | 146.08W |
| Cast Iron | 162.91W |
| Aluminum alloy | 150.98W |
| Copper/Aluminum | 178.09W |

Under the same condition, the simulation towards stainless steel radiator with different thickness is made. To apply the thickness of radiator with 0.02m and 0.03m into the model, accordingly, the results are shown in Table 18.

*Table 18. Heat transfer rate of stainless steel radiator with various thicknesses*

| **Thickness of radiator** | **Heat rate** |
|---|---|
| 0.01 | 146.08W |
| 0.02 | 138.83W |
| 0.03 | 132.20W |

# 6 CONCLUSION

In this study, three basic questions regarding conduction, convection, and radiation are solved successfully. As a foundation, the part of theoretical methods benefit on analyzing and solving. The author offers solutions of the three questions. By this means, readers can understand how to analyze and to solve the problems on heat transfer. Furthermore, the author applies Comsol Multiphysics software to solve three questions. Comparing the results from the theoretical method with Comsol Multiphysics software, it has been proved that Comsol Multiphgysics software can offer accurate analysis. Meanwhile, it is a very efficient tool for solving heat transfer problem, especially for those completed problems.

Based upon the simulation of the heat transfer process of radiator in a room, under the same condition, copper/Aluminum radiator has the best heat transfer ability. Considering that different material has different price, it is recommended to carefully choose material of the radiator.

Through the simulation on stainless steel radiator with different thickness, it is known that reduce the thickness can increase the heat transfer rate. Therefore, by reducing the thickness of radiator does not only increase the heat transfer rate but also save costs from material expenses.

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# APPENDIX 1

Property Values of Metals [4]

| Metal | Properties at 20 ° C | | |
|---|---|---|---|
| | ρ, kg/m3 | Cp, kJ/kg K | k, W/(m*K) |
| Aluminum | | | |
| Pure | 2707 | 0.896 | 204 |
| Al-Cu (94-96%Al, 3-5%Cu, trace Mg) | 2787 | 0.883 | 164 |
| Al-Si(85.5%Al, 1%Cu) | 2659 | 0.867 | 137 |
| Al-Si(78-80%Al, 20-22%Si) | 2627 | 0.854 | 161 |
| Lead | 11373 | 0.13 | 35 |
| Iron: | | | |
| Pure | 7897 | 0.452 | 73 |
| Wrought iron, 0.5%C | 7849 | 0.46 | 59 |
| Carbon steel (C≈0.5%) | 7833 | 0.465 | 54 |
| Carbon steel (C≈1.5%) | 7753 | 0.486 | 36 |
| Nickel steel (Ni ≈0%) | 7897 | 0.452 | 73 |
| Nickel steel (Ni ≈40%) | 8169 | 0.46 | 10 |
| Chrome steel (Cr = 0%) | 7897 | 0.452 | 73 |
| Chrome steel (Cr = 1%) | 7865 | 0.46 | 61 |
| Chrome steel (Cr = 20%) | 7869 | 0.46 | 22 |
| Chrome-Nickel steel (15%Cr, 10%Ni) | 7865 | 0.46 | 19 |
| Chrome-Nickel steel (20%Cr, 15%Ni) | 7833 | 0.46 | 15.1 |
| Tungsten steel (W=0%) | 7897 | 0.452 | 73 |
| Tungsten steel (W=5%) | 8073 | 0.435 | 54 |
| Copper: | | | |
| Pure | 8954 | 0.3831 | 386 |
| Aluminum bronze (95%Cu, 5%Al) | 8666 | 0.41 | 83 |
| Brass 70% (Cu, 30% Zn) | 8522 | 0.385 | 111 |
| Constantan (60% Cu, 40% Ni) | 8922 | 0.41 | 22.7 |
| Magnesium | | | |
| Pure | 1746 | 1.013 | 171 |
| Mg-Al (6-8%Al, 1-2% Zn) | 1810 | 1 | 66 |
| Molybdenum | 10220 | 0.251 | 123 |
| Nickel | | | |
| Pure | 8906 | 0.4459 | 90 |
| Ni-Cr (90%Ni, 10%Cr) | 8666 | 0.444 | 17 |
| Silver: | | | |
| Purest | 10524 | 0.234 | 419 |
| Pure(99.9%) | 10525 | 0.234 | 407 |

# APPENDIX 2

Properties of Nonmetals [4]

| Sbustance | Properties | | | |
|---|---|---|---|---|
| | Temperature ° C | k, W/(m*K) | ρ , kg/(m3) | c, kJ/(kg*K) |
| Brick: | | | | |
| Building brick | 20 | 0.69 | 1600 | 0.84 |
| Chrome brick | 200 | 2.32 | 3000 | 0.84 |
| Cement, portland | | 0.29 | 1500 | |
| Glass, Window | 20 | 0.78 | 2700 | 0.84 |
| Plaster, gypsum | 20 | 0.48 | 1440 | 0.84 |
| Sandstone | 40 | 1.83 | 2160-2300 | 0.71 |
| Wood | | | | |
| Balsa | 30 | 0.055 | 140 | |
| Cypress | 30 | 0.097 | 460 | |
| Fir | 23 | 0.11 | 420 | |
| Yellow pipe | 23 | 0.147 | 640 | 2.8 |
| Asbestons-cement | 20 | 0.74 | | |
| Balsam wool | 32 | 0.04 | 35 | |
| Corkboard | 30 | 0.043 | 160 | |
| Fiber, insulating board | 20 | 0.048 | 240 | |
| Glass wool | 23 | 0.038 | 24 | |
| Wood shavings | 23 | 0.059 | | |

# APPENDIX 3

Normal Total Emissivity of Various Surfaces. [4]

| Material | Temperature, ° C | Emissivity ε |
|---|---|---|
| | | |
| Aluminum | | |
| Commercial sheet | 100 | 0.09 |
| Al-surfaced roofing | 38 | 0.216 |
| Copper | | |
| Polished | 100 | 0.052 |
| Plate, heated long time | 25 | 0.78 |
| Gold | 227-627 | 0.018-0.035 |
| Iron and steel | | |
| Steel,polished | 100 | 0.066 |
| Iron,polished | 427-1027 | 0.14-0.38 |
| Cast iron | 22 | 0.44 |
| Lead | | |
| Unoxidized,99.96% pure | 127-227 | 0.057-0.075 |
| Gray oxidized | 24 | 0.28 |
| Magnesium | 275-825 | 0.55-0.20 |
| Molybdenum (massive, polished) | 100 | 0.071 |
| Nickel: | | |
| Polished | 100 | 0.072 |
| Nickel oxide | 650-1255 | 0.59-0.86 |
| Silver | | |
| Polished | 38-370 | 0.022-0.031 |
| Polished, pure | 225-625 | 0.02-0.032 |
| Stainless steels | | |
| Polished | 100 | 0.074 |
| Type 301 | 230-940 | 0.54-0.63 |
| Asbestos,board | 23 | 0.96 |
| Brick (red,rough) | 21 | 0.93 |
| Glass (smooth) | 22 | 0.94 |
| water | 0-100 | 9.95-0.963 |