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# Heat Transfer Analysis in Orthopedic Ovens for Use in Home Industry

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**Abstract.** The orthopedic oven is one of the tools used in the world of health. Until now, the orthopedic oven needs are still imported from other countries. The orthopedic oven is an oven that is used to heat plastic resins such as polypropylene quickly and evenly. The operation of this oven uses a large electric power and the purchase price is also relatively expensive so usually only used in large orthopedic workshops. This makes meeting the needs of the use of the orthopedic oven is limited so there needs to be an orthopedic oven design with adequate power for the home industry at a low cost. This design analysis using the calculation of heat transfer that occurs in the oven such as internal force convection, conduction, or un-steady conduction to obtain critical wall thickness values that must be used to minimize heat loss that occurs and the time needed to heat polypropylene resin. Based on the analysis of data calculations performed, obtained to reduce the heat loss that occurs need to use a gypsum board (k=0,132 W/m0C) with a thickness of 0,28 m, and the time required to heat the polypropylene to reach a temperature 185°C is 20,6 minutes.

## INTRODUCTION

Orthopedic aids are medical devices designed to treat musculoskeletal problems; this tool is used to align, correcting position, supporting body, stabilizing, and protecting certain parts of the body (especially muscles, joints, and bones) as they heal from accident pain (injury). These medical tools are often given to patients for use during the recovery and rehabilitation process.

Many specialized medical fields use orthopedic implant devices, including those related to injury rehabilitation and prevention, postoperative care, osteoarthritis care, and others. A trained medical professional can determine the appropriate type of orthopedic implant device for the patient, as well as the size, type of support, function, and level of stability or protection. Orthopedic implants use several types of materials such as metals, ceramics, and polymers. The polymer materials commonly used are polyethylene, polypropylene, PET, and PMMA. Before being used, this polymer material must be preheated so that it is easily formed according to the required implant shape [1].

Orthopedic ovens are ovens that are used to heat polymer materials such as polyethylene and polypropylene so that they are softer and easier to shape. After the heating process in the oven is carried out, it is followed by the formation of the required orthopedic implants. In the heating process in the oven, heat transfer occurs between the heating components and air and the plastic polymer. Heat transfer occurs due to temperature differences, where heat flows from an object with a high temperature to an object at a lower temperature. Heat transfer in this case occurs in the heater, the air in the oven, the walls, and the plastic polymer that is heated. A heater or Heat Exchanger is a heat exchanger which functions to exchange heat between two fluids at different temperatures without mixing the two fluids [2]. This process occurs by utilizing the heat transfer process of two fluids with different temperatures. The process of heat transfer can occur in three ways, namely: conduction, convection, and radiation [3].

The heat transfer process by a heat exchanger is influenced by several things, namely the coefficient value of the heat transfer, the thickness of the insulation material used, the intake velocity of cold or hot air, Reynold number, Prandtl number, and Nusselt number which depend on the type of flow and fluid properties [4].

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The speed of fluid flow in the oven affects the heat transfer process that occurs in it, the faster the fluid flow rate, the greater the power needed to heat it. The thickness of the insulation material also affects the energy required in the oven heating process, the thicker the insulation material used, the smaller the heat loss that occurs but the greater the manufacturing costs, therefore analysis is needed to obtain the thickness of the insulation material used. The results of the analysis carried out were translated into an orthopedic oven design using Solidworks software.

In general, orthopedic ovens are large and use a large amount of electrical power, so that orthopedic ovens are usually only used in small-scale orthopedic workshops. Home industry scale workshops cannot use this orthopedic oven because it requires large electrical power, therefore it is necessary to analyze orthopedic oven designs with power that can be used for the home industry. In designing an oven, a design process is needed that requires supporting theories which will be discussed below:

## Heat

Heat is defined as the heat energy possessed by an object. In general, to detect the heat possessed by an object, namely by measuring the temperature of the object, if the temperature is high, the heat contained by the object is very large, and vice versa if the temperature is low, the heat contained little. based on Equation 1, the amount of heating value needed by an object or substance depends on 3 factors, that are:

A. Mass
B. Specific heat
C. Temperature changes

So that mathematically it can be formulated:

$$Q = mc(T2 - T1) \tag{1}$$

"Energy cannot be created or destroyed, energy can only be converted from one form of energy to another." Heat is a form of energy that can move and also change form into other forms of energy. Based on the law of conservation of energy, electrical energy can change to heat energy and vice versa. In this study, there was a change in electrical energy and heating energy only. When the heating element is electrified for a certain time, some of this electric current will turn into heat energy. When two objects with different temperatures join together, they will exchange internal energy until the temperature of the two objects is equal. The amount of energy channeled is the amount of energy exchanged [5]. The amount of electrical energy used can be calculated using Equation 2. The energy in this is directly proportional to the temperature of the object. The amount of electrical energy that is converted or absorbed is equal to the heat produced. This requires that the equilibrium of electrical and heat energy equilibrium be met as shown by Equation 3.

$$\mathrm{W} = \mathrm{Pt} \tag{2}$$

$$Pt = mc(T2 - T1) \tag{3}$$

According to Black's principal theory, if two objects with different temperatures are put together or mixed, there will be a flow of heat from an object with a high temperature to another object which has low temperature. This flow will stop until there is a thermal balance between the two objects. Those that release heat are objects that have high temperature and those that receive heat are objects that have low temperature

## Heat Exchanger

The science of predicting energy transfers that occur due to differences in temperature between objects or materials. The science of heat transfer is not only trying to explain how the heat moves from one object to another object but also studies heat transfer under certain conditions [6]. Generally, heat transfer takes place in three ways, namely:

### *Conduction*

Conduction is the process of transferring heat from one part of a solid object or material to another. In conduction heat transfer, no metallic material is transferred. What happens is metal molecules that are placed on the flame hit the molecules that are nearby and give some of their heat [3].

The process of conducting conduction heat transfer is from a high temperature to a low temperature using a medium (solid, gas, and liquid) directly. Based on Fourier's Law [7] the amount of conduction heat transfer can be calculated with Equation 4 and the resistance of conduction thermal can be calculated with Equation 5

$$q" = kAdT/dx \tag{4}$$

Thermal conduction resistance on flat walls

$$Rconduction = (T' - T)/q" = L/kA \tag{5}$$

For a one-dimensional system, there are two conditions, namely:

1. In a steady-state, if the properties do not change with time, then the problem is simple, and we only need to integrate the equation and transfer (substitution) the correct values to solve the problem.
2. Unsteady state, which is when the temperature changes with time

*Convection*

Convection heat transfer is heat transfer that occurs because of temperature differences that cause intermolecular random motion and bulk motion of a fluid. The faster the fluid moves, the greater the convection heat transfer rate that occurs [7]. The combined heat transfer transport process of heat conduction, energy storage, and mixing motion. Convection is very important as a process for transferring energy through the surface of a solid and a liquid or a gas [8].

Convection heat transfer needs to take into account the velocity of the fluid as a heat transfer. The temperature gradient here also depends on the rate at which the fluid carries heat from the heating source, so a high speed will cause a large temperature gradient too, and so on [8]. The convection heat transfer value can be calculated using Equation 6, and the convection thermal resistance can be calculated by Equation 7.

$$q" = hA(T' - T) \tag{6}$$

$$RConvection = (T' - T)/q" = 1/hA \tag{7}$$

The convection heat transfer coefficient h varies with the type of flow fluid and Reynold's number, the physical properties of the fluid, also varies depending on the convection heat transfer mechanism and temperature. The characteristic properties of the fluid can be characterized based on the temperature film, the temperature of the film can be calculated using Equation 8. The heat flux of the solid surface will depend on the surface temperature (Tw) and the fluid temperature (Tf), but it is usually assumed that (ΔT = Tw - Tf) the important one. However, if the fluid properties change significantly in the convection region, then the absolute temperature Tw and Tf can also be important factors in the correlation [9].

$$Tfilm = \frac{Tw - T\infty}{2} \tag{8}$$

Research conducted by Davies M. R. D [10] states that changes in free-air temperature affect the Nusselt number where the higher the temperature of the free air in a closed room, the lower the Nusselt number. According to Hilbert's theory, the value of the Nusselt number which shows the relationship between the heat transfer ratio of convection and conduction can be calculated by Equation 9 and the constants C and N vary with the Reynold value according to Table 1. The analysis of convection can be done by two approaching, by steady state and unsteady/transient Transient convection is of fundamental interest in many industrial and environmental situations such as air conditioning systems, human comfort in buildings, atmospheric flows, motors, thermal regulation process, cooling of electronic devices, security of energy systems [11].

$$Nu = \frac{hD}{k} = C\ (Re\ f)^n x Pr^{0,33} \tag{9}$$

**TABLE 1.** Hilbert's Theorem Table

| $R_{ed.f}$ | *C* | *N* |
|---|---|---|
| 0,4 – 4 | 0,989 | 0,330 |
| 4 – 10 | 0,911 | 0,385 |
| 40 – 4000 | 0,683 | 0,466 |
| 4000 – 40000 | 0,193 | 0,618 |
| 40000 – 400000 | 0,0266 | 0,805 |

*Radiation*

Radiation is the process of transferring heat from one object to another without going through the medium. In the radiation theory, it is explained that the heat that passes from one object to another is emitted by electromagnetic waves so that the transfer process does not require any medium at all. Even if the two objects are separated by a vacuum, heat will still move through the emission of electromagnetic waves. The common feature of such processes is the radiative heat transfer, dominating at high temperatures. The radiative heat transfer equation (RTE) is a first order integro-differential equation governing the radiation intensity [12].

The rate of radiant heat transfer to an object is influenced by several things, namely the surface temperature that emits and receives radiation, the emissivity of the radiated surface, reflection, absorption and transmission, and the view factor between emitting and receiving radiation [9].

The radiation heat transfer rate can be calculated by Equation 10.

$$q = \sigma e A T^4 \tag{10}$$

## METHODOLOGY

The research method used is development research. This development research was conducted to analyze the heat transfer that occurs in an orthopedic oven and to analyze the thermal conductivity of the working fluid. Analysis of the calculation of heat transfer that occurs in the oven aims to determine several parameters in the oven design and the specifications of the heater used in the design process. The results of the analysis of this study are followed by an orthopedic oven design which can later be used to become the basis for making orthopedic home industry ovens. The oven data collection technique is carried out through the calculation analysis method, this calculation data analysis is adjusted to the operating conditions of the orthopedic oven from the ottobock oven for orthopedic workshops [13], the data obtained is then implemented in the form of an orthopedic oven design using Solidworks 2016.

## ANALYSIS AND DISCUSSION

In accordance with the method listed above, the analysis of the calculation of heat transfer that occurs from the heating element in the oven heating room, the heat transfer analysis on the oven wall, and the calculation of the time it takes for the oven to reach the melting point of the polypropylene.

### Heat Circulation from Heater to Orthopedic Oven Heating Chamber

From observations of oven heaters, generally using a tubular heater electrical element type, in this study using a tubular heater as in Figure 1 with the following specifications:

1. Diameter: 11.5 mm x 2000 mm
2. Electricity Requirements: 220 Volt-2000 Watt
3. Mass: 1 Kilogram

**FIGURE 1.** Tubular Heater 220 Volt 2000Watt

Characteristics of fluid in characterization based on the temperature of the fluid film. To reach a temperature of 300oC, based on Equation 8, you can get the fluid film temperature of:

$T_f = (T_w - T_\infty)/2 = (23+300)/2$

$T_f = 161{,}5^o$ C

The blower used is (8x8) cm2 220 Volt 720 rpm so that the speed of fluid flow in the oven = 3m / s

Using the interpolation method from table properties of air "Fundamental of Heat and Mass Transfer, C.P. Kothandaraman, Third Edition", we find the properties of air from Table 2.

**TABLE 2.** Properties of air inside of the oven

| | |
|---|---|
| $\rho_f$ | 0,7817 kg/m$^3$ |
| $k_f$ | 0,037695 W/m°C |
| $\mu_f$ | 25,2415 x 10$^6$ kg/m.s |
| $Pr_f$ | 0,68107 |
| $Re_f$ | 1068,425 |

By using Equations 6 and 9 we calculate the Nusselt number and convection heat transfer inside of the oven as Table 3.

$$q" = hA(T' - T)$$

$$Nu = \frac{hD}{k} = C\ (Re\ f)^n x Pr^{0,33}$$

**TABLE 3.** Calculation convection heat transfer inside of the oven

| | |
|---|---|
| Nu | 15,51 |
| h | 50,832 W/m2oC |
| Q convection | 2034,81 Watt |

## Analysis of Heat Transfer Against Oven Body

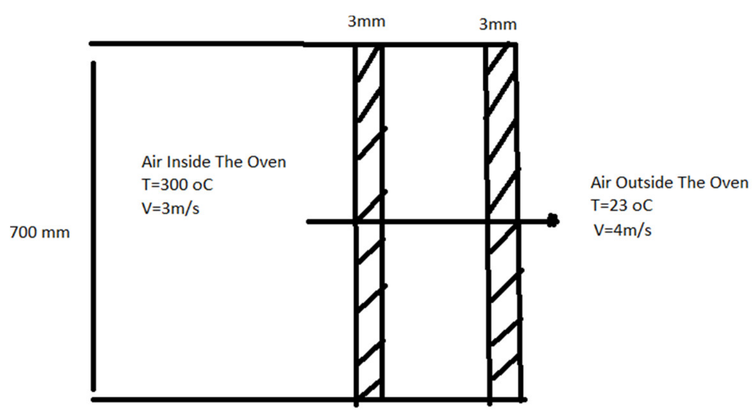


**FIGURE 2.** Part of Oven's Body

The oven body is made with 2 pieces of 3 mm thick stainless steel plate which is covered with a gypsum board as in figure 2. From the data above, we can analyze how thick the gypsum is needed so that the temperature on the outer wall is not more than 35° C

We assumed:

a. Steady condition
b. There is a conduction heat transfer through the wall
c. Heat transfer with radiation is negligible.
d. There is convection heat transfer to the entire wall.
e. Thermal conductivity of the materials used:
   Stainless steel plate = 15,1 W/m°C
   Gypsum Board = 0,132 W/mK
f. Assume Tc = 35°C, so that not too much heat comes out of the oven

By using the air property table "Fundamentals of Heat and Mass Transfer, C.P. Kothandaraman, Third Edition ", obtained for air properties in Table 4.

TABLE 4. Properties of air T=300°C

| | |
|---|---|
| $v_w$ | 48 x 10^-6 $m^2/s$ |
| $k_w$ | 0,0448 W/m°C |
| $Pr_f$ | 0,680 |
| $Re_f$ | 43.750 |
| Nu | 73,341 |
| h | 4,69 $W/m^{2o}C$ |

The temperature outside of the oven is T∞=23$^0$C, Velocity of air = 4 m/s

From the table of air properties the book "Fundamentals of Heat and Mass Transfer, C.P. Kothandaraman, Third Edition "using the interpolation method obtained the properties of air outside the oven as shown in Table 5.

TABLE 5. Properties of air outside of the oven

| | |
|---|---|
| $v_w$ | 15,718 x 10^-6 $m^2/s$ |
| $k_w$ | 0,0265 W/m°C |
| $Pr_f$ | 0,7016 |
| $Re_f$ | 178.139,7 |
| Nu | 249,32 |
| h | 9,438$W/m^2\,^0C$ |

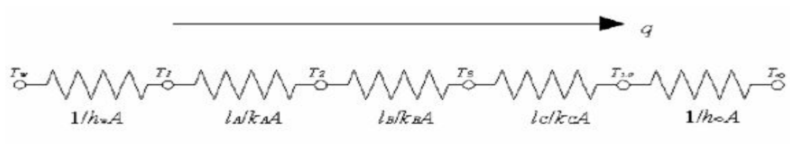


**FIGURE 3.** Oven Electrical Analogy for Oven Walls

Heat propagation on the oven wall can be analogized as shown in Figure 3. By using equation 5 and 7 with the properties of air both inside and outside of the oven and properties of wall's with insulation material, we calculate the value of insulation thickness for use in this oven and the heat loss from the oven, assume the outer wall of the oven temperature is 35°C.

$$Rconduction = (T' - T)/q = L/kA$$
$$RConvection = (T' - T)/q = 1/hA$$

Q = $(T_\infty - T_w)$ / U

$h_\infty$ (Tc- $T_\infty$) = $(T_w - T_c)$/ [ (1/hw) + (La/KAa) + (Lb/KAb) + (Lc/Kc)]

We found:

TABLE 6. Thickness of insulation wall

| | |
|---|---|
| Lb (Thickness of insulating material for the sidewall) | 0,281 m |
| Q heat loss through sidewall | 65,4 watt |
| Lb (Thickness of Insulating material for the upper wall | 0,28 m |
| Q heat loss through upper wall | 108 Watt |
| Lb (Thickness of Insulating material for the front wall | 0,287 m |
| Q heat loss through front wall | 95 Watt |

## Analysis of Heat Spread Received by Polypropylene Resin

Heat is received by polypropylene as shown in Figure 4 in the oven, to heat polypropylene in the oven until the plastic melts take time. The time taken to heat polypropylene to thickness can be calculated using Equation 3.

$$Pt = mc(T2 - T1)$$

With 2000Watt oven power to heat a polypropylene sheet (1,2x0,7 m2) with a thickness of 10 mm to its melting point (185oC) takes 20.6 minutes.

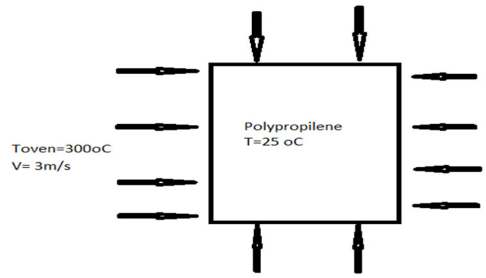


**FIGURE 4.** *Polypropylene* Inside of Oven

| Plastic | Temperature range | | Heating time |
|---|---|---|---|
| | PE 200 | PP-H/PP-C | |
| 3 mm | 165 °C | 185 °C | 3 – 5 min |
| 4 mm | 165 °C | 185 °C | 4 – 6 min |
| 5 mm | 165 °C | 185 °C | 5 – 8 min |
| 6 mm | 165 °C | 185 °C | 6 – 9 min |
| 8 mm | 165 °C | 185 °C | 8 – 12 min |
| 10 mm | 165 °C | 185 °C | 10 – 15 min |
| 12 mm | 165 °C | 185 °C | 12 – 18 min |
| 15 mm | 165 °C | 185 °C | 15 – 22 min |

**FIGURE 5.** Operating Condition of Oven Orthopedic 4000 Watt

Figure 5 above shows the operating condition data of the ottobock orthopedic oven [12], the operating conditions of the oven used are: using a 4000 W oven heats a polypropylene sheet of varying thickness as shown in Figure 5.

By using Equation 3, we get a graph of the power used against the heating time of polypropylene in the oven, the greater the power used, the faster the heating process takes place, as in Figure 6.

$$Pt = mc(T2 - T1)$$

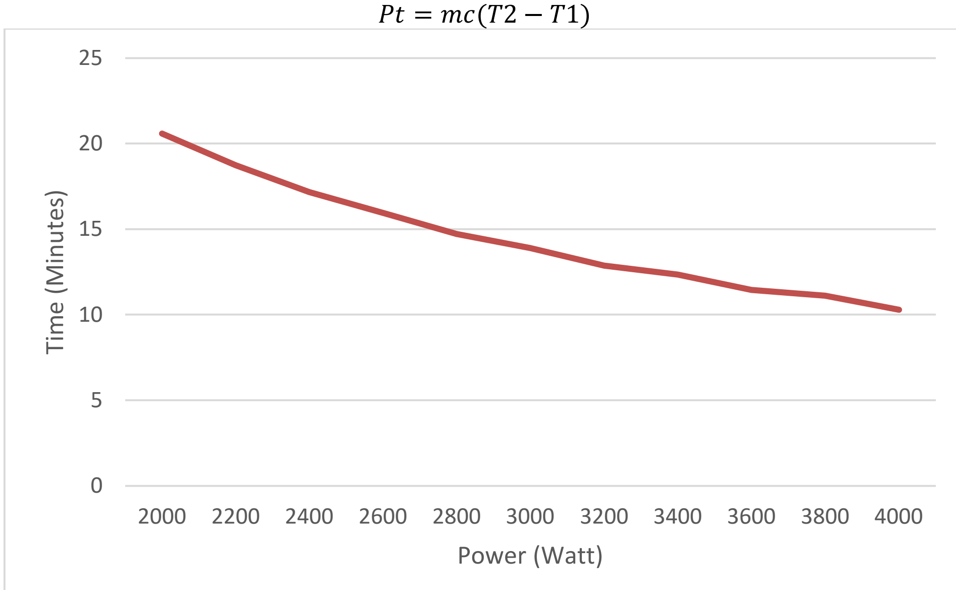


**FIGURE 6** Relation of Oven Power to Heating Time

From the analysis we can calculate the heat are needed to increase the temperature of polypropylene is:
Qtotal = Qconvection + Q heat loss
Qtotal = 2300 Watt

From the heat transfer analysis of the orthopedic oven, the specifications and dimensions of the oven were obtained as Table 7, which were designed using the Solidworks application as Figure 7.

**TABLE 7.** Dimension and Specification

| No. | Unit | Specification |
|---|---|---|
| 1. | Dimension | (0,7 x 1,2 x 0,8) $m^3$ |
| 2. | Tubular Heater | 220 Volt-2000-Watt, 11,5 mm x 2000 mm |
| 3. | Blower | 220v 8 x 8 |
| 4. | Insulating Material | Gypsum Board |
| 5. | Oven's Material | Stainless Steel 304, Thickness 3mm |

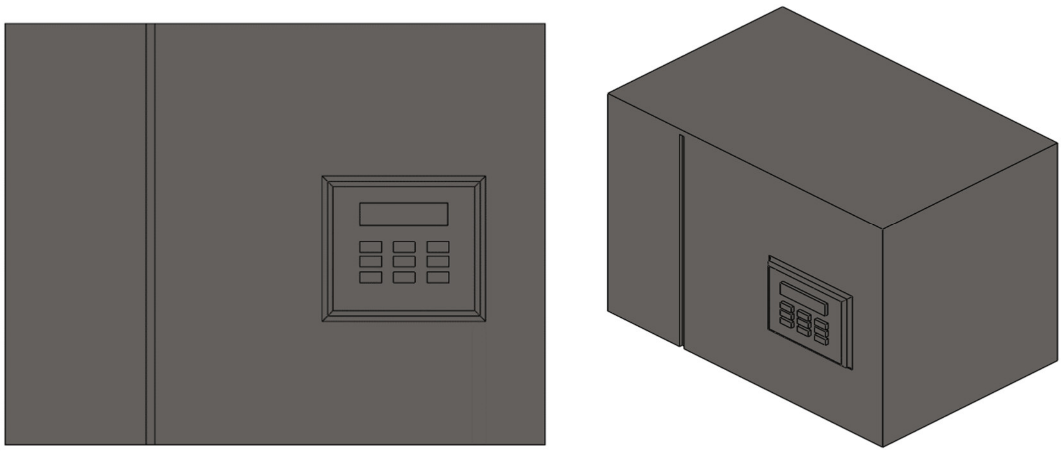

**FIGURE 7.** Design of Orthopedic Oven

## CONCLUSION

Based on the calculation data and analysis that has been done, it can be concluded:

Stable heat must be generated by the heater to produce even heat so that the polypropylene heating process can be faster and more efficient. To produce that heat the oven must have a good construction unit such as the oven body, fan (blower), heater, and other parts. The use of insulation to reduce the occurrence of heat loss, the heat required to heat polypropylene in the oven is 2300Watt and the thickness of the gypsum board used as an insulation material is 0.28 m. The thicker the insulation material used, the smaller the heat loss that occurs and the more efficient the heat transfer process in the oven. The length of time it takes for the oven to heat the polypropylene in the oven is 20,6 minutes.

## ACKNOWLEDGMENT

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## NOMENCLATURE

| | |
|---|---|
| Q | Heat required [J] |
| M | Mass [kg] |
| c | Specific heat [J/kg K] |
| (t2-t1) | Temperature changes [K] |
| W | Electrical energy [Joule] |
| P | Electricity Power [Watt] |
| t | Times [second] |
| q" | Heat flow [W/m²] |
| q | Heat transfer rate [Watt] |
| R | Thermal resistance [K/W] |
| h | Convection Coefficient [W/m²K] |
| A | Area [m²] |
| k | Conductivity [W/m] |
| Nu | Nusselt Number |
| $\sigma$ | Boltzmann constant (5,67 x $10^{-8}$W$m^{-2}K^{-4}$) |
| e | Emissivity. |
| T | Temperature [C] |