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Finned Electric Motor with Prescribed Heat Fluxand Influence of the Internal and External Heat Convection Coefficients on the Temperature of the Core

Marcus V. F. Soares [α] & Élcio Nogueira [σ]

Abstract- One of a major objective is to analyze the effect of internal and external convection coefficients in the heat transfer generated by electric motors and characterize intervals of feasible values, in practical terms, for these coefficients. Another objective is to determine the motor core temperature, considering the environmental and operational conditions of the motor installation and the heat flux Q_0 (fixed) in the fins. To achieve the objectives were developed analytical solutions for determining the temperature variations in the fins, performance and electric motor efficiency, considering heat flow constant at the base of the fins and the possible variations in temperature of surround media. The heat flux at the base of the fins, in this case, is the minimum necessary for satisfactory electric motor performance and the core temperature is within the safety range stipulated by the manufacturer. The obtained results characterize a range of possible values for the inner and outer heat transfer coefficients. These values guarantee the lowest value for the heat transfer rate required for efficient heat removal at the given environmental temperature.

Keywords: finned electric motor; constant heat flow; efficiency; efficacy.

I. Introduction

The electric motor is responsible for the transformation of electric energy into mechanical energy, which is the main end-use of electric energy in industries in general, and its wide use in this sector is due to its simple construction and wide versatility in applying loads.

Factors that allow electric motors to lose up to 4% of their performance over their lifetime are improper installations, lack of regular maintenance, cleanliness and quality lubrication (Cardoso et. Al., 2009). Therefore, overheating the electric motor and consequently burning it is a problem for maintenance personnel, since heat produced by the electric motor must be dissipated efficiently, avoiding overheating and consequent burning. The high temperatures of the installation environment and the inefficient heat dissipation generated by the difference in net power supplied by the motor and power absorbed in the line is the main cause of overheating (Santos, Rafael Simões, 2011).

Fins or the extended surfaces are extensively used in engineering applications to increase the heat transfer efficiency of surfaces, and are of vital importance in the design of heat exchange devices in different fields of applications in order to provide an enhanced heat transfer effect through an increase in the total heat exchange area (Campo, A.; Kundu, B.,2017), (Incropera, Frank P. Et Al., 2008), (Santos, T. A. M., 2017). Once the temperature distribution through the fin is known, the heat transfer rate and the efficiency can be readily determined.

In electric motors, it is common to use extended surfaces, which increase the exchange area as a mechanism for heat transfer optimization. In fact, an important industrial application of fins occurs in electric motors and are of vital importance in the industry as they are used in machines of all types, including, for example, computer ventilation and other electronic equipment. A well-dimensioned finned ventilation system can contribute to energy savings.

The heat dissipation is directly associated with efficient ventilation, the temperature difference between the engine housing surface and the medium (in this case, the air surrounding the engine), the total heat exchange area of the engine housing and of extended surfaces (fins). Important feature is the geometry of the fins, as they have a great influence on the area available for exchange and, in order to heat transfer as good as possible, the construction material of these fins must have high thermal conductivity, such as aluminum and copper (Duarte, Denise Freire; Novais, Ariane Silva; Nogueira, Élcio, 2012), (Novais, Ariane; Chagas, R. D. F.; Nogueira, Élcio, 2014), (Marcus Vinicius Ferreira Soares, 2015), (Voigdlener, Thiago, 2004).

Ventilation depends directly on the internal and external convection heat transfer to which the motor is subjected. This dependence is because the heat exchange occurs between a moving fluid (air) and the motor surface (housing), which are at different temperatures. The air moves due to the internal and

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external convection process causing a random molecular displacement on the surface. According to Ordenes (2008), the convection coefficient is a proportionality constant that considers several factors, including surface geometry and the nature of the flow.

Novais and Comitra (2014) showed that one of the factors that contribute to burning is the thermal resistance that exists between the housing and the motor core. According to Moreira (2012), besides the convection acting in the region outside the motor housing, and its respective convection coefficient, there is also the convection in the internal region and the resistance associated with the conduction process that occurs in the air layer, between the core and the motor housing.

The contact interface between the motor wall and its insulation is promoted by a mechanical union that generates a thermal resistance due to imperfect contact, resulting from small roughness and undulation. In this region, conduction occurs at the contact points and conduction through the trapped fluids in the interstices of roughness and undulation. However, it is important to note that some motors do not use this contact interface between the motor wall and its insulation, being air the only element that serves as thermal resistance between the motor core and the housing.

Thus, we have to determine two convection coefficients, one of them referring to the external region and the other to the internal part of the motor housing, the latter is also dependent on the microscopic imperfections on the surfaces and the contact pressure of the materials, the fluid contained in the interstices, of the applied oxide film and the metallic shim involved. This latter convection coefficient is undoubtedly the most complex of the two processes and the most difficult to obtain experimentally.

Although the internal resistance is crucial for the correct motor thermal sizing, the usual theoretical models still consider the temperature at the fin base attached to the motor housing equal to the motor core temperature.

In Table 1 below, some physical and geometrical characteristics of the engine.

Table 1: Engine Data

Power	1 cv
Number of Poles	4
Motor Outer Diameter	139,60 mm
Engine Width	130,13 mm
Number of Fins	32
Fin Base Width	5,84 mm
Fin Height	17,00 mm
Maximum Ambient Temperature	40 °C

II. Theoretical Analysis

Analytical solutions for temperature profiles were developed considering constant heat flux in the fins, and constant thermo physical properties. Variations were also simulated between the motor housing construction materials: cast iron and aluminum.

In this context we have the Ordinary Differential Equation (E.D.O.) of the rectangular profile fin, described by the equation below:

$$\frac{d^2T(r)}{dr^2} = \frac{h.A_l}{k.V}[T(r) - T_\infty] \quad 01$$

at where: $A_l = P_b.LeV = A_b.L$

$$\frac{d^2T(r)}{dr^2} = \frac{h.P_b}{k.A_b}[T(r) - T_\infty] \quad 02$$

$$\theta(r) = T(r) - T_\infty \quad 03$$

$$\frac{d^2\theta(r)}{dr^2} = \frac{h.P_b}{k.A_b}\theta(r) \quad 04$$

making $m^2 = \frac{h.P_b}{k.A_b}$ and substituting in equation (3) we have:

$$\frac{d^2\theta(r)}{dr^2} = m^2.\theta(r) \quad 05$$

$$\text{as}\, m^2 = \frac{h.P_b}{k.A_b} \rightarrow m = \sqrt{\frac{h.P_b}{k.A_b}}$$

Whose E.D.O general solution is:

$$\theta(r) = C_1.cosh(mr) + C_2.senh(mr) \quad 06$$

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1st boundary condition: r = 0

$$-k.\frac{d\theta}{dr} = Q_0 \quad (07)$$

2nd boundary condition: r = L

$$-k.\frac{d\theta}{dr} = h_2.\theta_L \quad (08)$$

At where

$$\theta_L = \theta(L) = T(L) - T_\infty \quad (09)$$

$$\frac{d\theta}{dr} = C_1.m.senh(mL) + C_2.m.cosh\,(mL) \quad (10)$$

From the first boundary condition (r = 0), we must:

$$-k.[C_1.m.senh(m.0) + C_2.m.\cosh(m.0)] = Q_0 \quad (11)$$

as $senh(0) = 0$ e $cosh(0) = 1$, we have:

$$-k.[C_2.m] = Q_0 \quad (12)$$

$$C_2 = -\frac{Q_0}{.k\ m} \quad (13)$$

From the 2nd boundary condition (r = L), we must:

$$-k.[C_1.m.senh(mL) + C_2.m.cosh\,(mL) = h_2.[C_1.cosh(mL) + C_2.senh(mL)\,] \quad (14)$$

$$-\frac{k}{h_2}.C_1.m.senh(mL) - \frac{k}{h_2}C_2.m.cosh(mL) = C_1.cosh(mL) + C_2.senh(mL) \quad (15)$$

$$-C_1\left[\frac{k.m}{h_2}.senh(mL) + \cosh(mL)\right] = C_2\left[\frac{k.m}{h_2}.\cosh(mL) + senh(mL)\right] \quad (16)$$

$$C_1 = -C_2.\frac{\left[\frac{k.m}{h_2}.\cosh(mL) + senh(mL)\right]}{\left[\frac{k.m}{h_2}.senh(mL) + \cosh(mL)\right]} \quad (17)$$

$$C_1 = \frac{Q_0}{k.m}\cdot\frac{\left[\frac{k.m}{h_2}.cosh(mL) + senh\,(mL)\right]}{\left[\frac{k.m}{h_2}.senh(mL) + cosh\,(mL)\right]} \quad (18)$$

$$Q_0 = 0{,}25.\left[\frac{\left(\frac{750}{32}\right)}{A}\right] \quad (19)$$

Q_0 is the flow prescribed on the fins and A is the area of the fin. Note that 750 W is the engine power. The calculated value of Q_0 for the motor studied is 7709.7 W / m^2.

To determine the motor core temperature, we have:

$$\dot{q} = \frac{T_M - T_b}{\frac{1}{h_1A} + \frac{\ln\left({D_2}/{D_1}\right)}{2\pi KL}} \quad (20)$$

$$A = \pi.D_1.L \quad \text{e} \quad D_1 = D_2 - 2.E_0$$

$E_0 = Motor\ wall\ thickness$

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$$\frac{\dot{q}}{A} = \frac{T_M - T_b}{\frac{1}{h_1} + \frac{A.\ln\left(D_2/D_1\right)}{2\pi KL}} \quad (21)$$

$$\frac{\dot{q}}{A} = Q_0 = \frac{T_M - T_b}{\frac{1}{h_1} + \frac{D_1.\ln\left(D_2/D_1\right)}{2K}} \quad (22)$$

$$Q_0 \cdot \left[\frac{1}{h_1} + \frac{D_1.\ln\left(D_2/D_1\right)}{2K}\right] = T_M - T_b \quad (23)$$

$$T_M = T_b + Q_0 \cdot \left[\frac{1}{h_1} + \frac{D_1.\ln\left(D_2/D_1\right)}{2K}\right] \quad (24)$$

where T_b is the temperature at the base of the fin, which depends on the operating conditions, i.e. external temperature T_∞ and external convection coefficient h_2.

III. Results and Discussion

The Table 2 shows the numerical values for motor core temperature with h_2 = 1000 W/ (m^2.ºC) and h_1 e T_∞ as variables.

We analyzed the temperatures ambient strictly below 45 °C for cast iron and aluminum materials. The data in Table 2 and Figure 1, related to the internal and external heat transfer coefficients, show that under the best possible condition [h2 = 1000 W / (m². ° C)], there is no considerable difference between the analyzed materials.

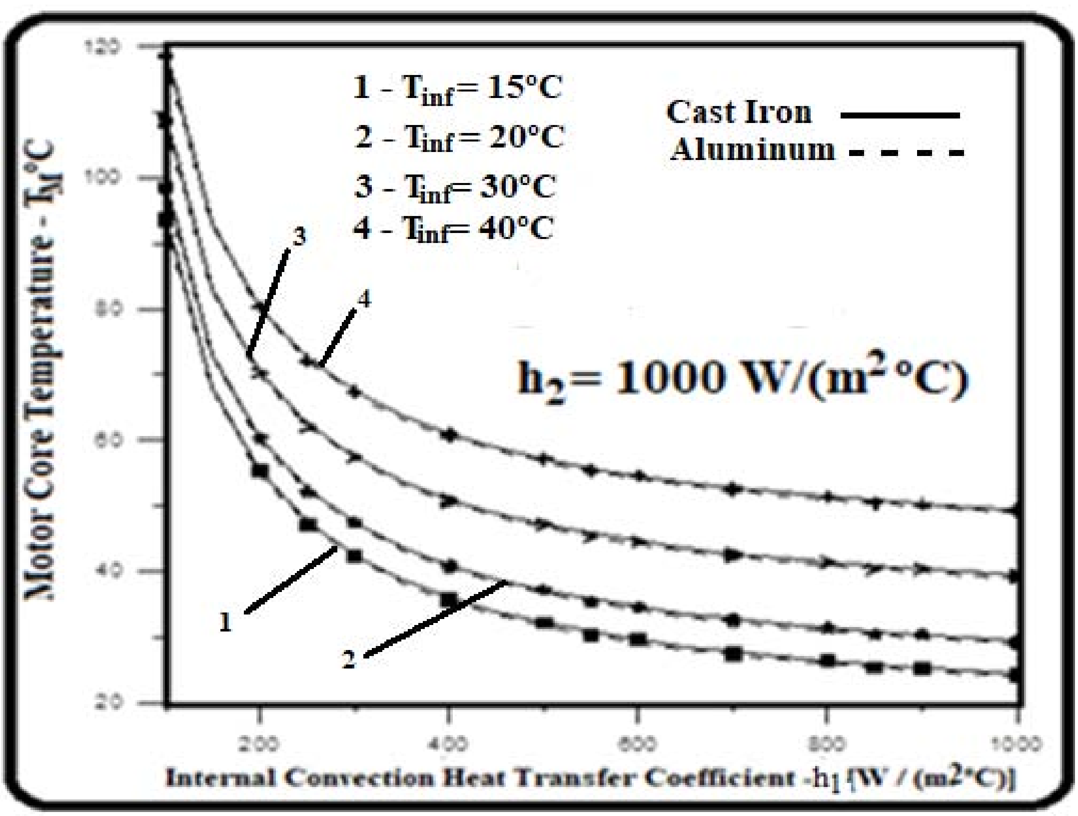

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Figure1: Motor Core Temperature - h_1 x T_M

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Table 2: Motor Core Temperature (T_M) versus Internal Convection Coefficient (h_1) h_2 = 1000 W/ (m^2 °C)

h1 W/(m²°C)	T_∞ = 15 Iron Cast	°C Al	T_∞ = 20 Iron Cast	°C Al	T_∞ = 30 Iron Cast	°C Al	T_∞ = 40 Iron Cast	°C Al
100	93,86	93,40	98,86	98,40	108,86	108,40	118,86	118,40
150	68,16	67,70	73,16	72,70	83,16	82,70	93,16	92,70
200	55,31	54,85	60,31	59,85	70,31	69,85	80,31	79,85
250	47,60	47,14	52,60	52,14	62,60	62,14	72,60	72,14
300	42,46	42,00	47,46	47,00	57,46	57,00	67,46	67,00
350	38,79	38,33	43,79	43,33	53,79	53,33	63,79	63,33
400	36,04	35,58	41,04	40,58	51,04	50,58	61,04	60,58
450	33,90	33,43	38,89	38,43	48,89	48,43	58,89	58,43
500	32,18	31,72	37,18	36,72	47,18	46,72	57,18	56,72
550	30,78	30,32	35,78	35,32	45,78	45,32	55,78	55,32
600	29,61	29,15	34,61	34,15	44,61	44,15	54,61	54,15
650	28,62	28,16	33,62	33,16	43,62	43,16	53,62	53,16
700	27,78	27,32	32,78	32,32	42,78	42,32	52,78	52,32
750	27,04	26,58	32,04	31,58	42,04	41,58	52,04	51,58
800	26,40	25,94	31,40	30,94	41,40	40,94	51,40	50,94
850	25,83	25,37	30,83	30,37	40,83	40,37	50,83	50,37
900	25,33	24,87	30,33	29,87	40,33	39,87	50,33	49,87
950	24,88	24,42	29,88	29,42	39,88	39,42	49,88	49,42
1000	24,47	24,01	29,47	29,01	39,47	39,01	49,47	49,01

For analysis purposes, a maximum engine core working temperature of 98 ° C is assumed. The manufacturer sets the maximum operating temperature equal to 120 ° C.

Analyzing Figure 2, for the external temperature of 40 ° C, we have that, for Cast Iron the motor to work in the acceptable temperature range, the value of h_2 must be greater than or equal to 200 W/ (m^2. °C).

For the value of h_1 = 200 W / (m^2. ° C), shown in Figure 3, the motor works at the limit established in the research and we can conclude that the motor works properly for values of h_1 above 200 W / (m^2. ° C).

Analyzing Figure 4, for the external temperature of 40 ° C, we arrive at the following conclusions: for h_1 = 100 W / (m^2. ° C) the motor temperature is equal to 128.61 ° C, which goes beyond the limit value. From research of 98 ° C. In the same Figure 4, for h_1= 200 W / (m^2. ° C) the motor temperature is equal to 90.06 ° C, below the search limit value. The value of h_1 = 200 W / (m^2. ° C) is feasible and achievable in natural ventilation.

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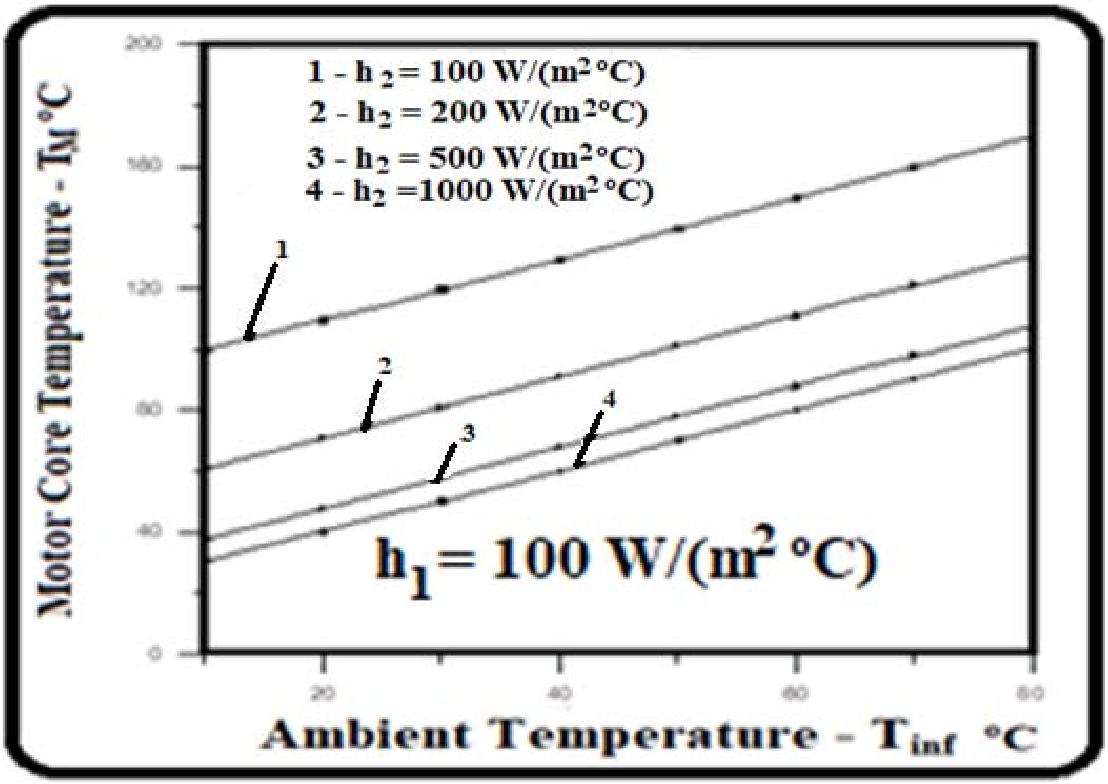

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Figure 2: Motor Core Temperature – T_{inf} x T_M

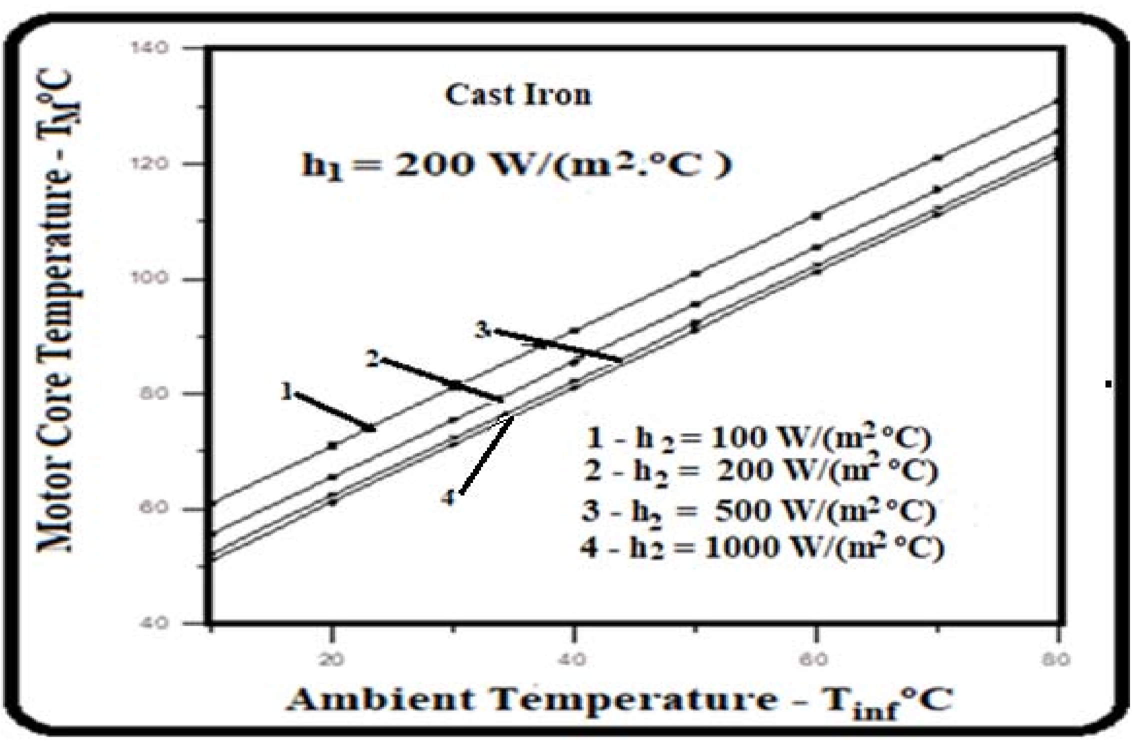

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Figure 3: Motor Core Temperature – T_{inf} x T_M

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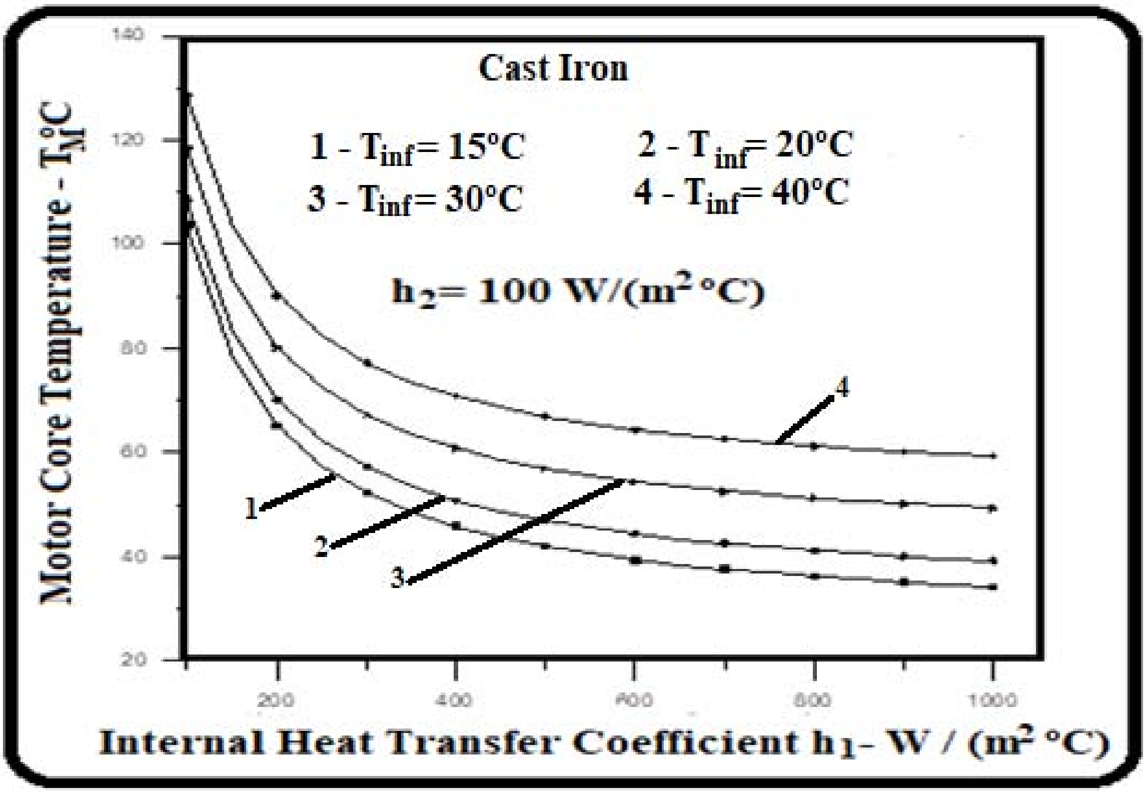

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Figure 4: Motor Core Temperature - h_1 x T_M

Looking at Figure 5 for the external temperature of 40 ° C, we arrive at the following conclusions: for h_1 = 150 W / (m². ° C) the motor temperature is equal to 97.48 ° C, very close to 98 ° C, but already below search limit. In the same Figure 5, for h_1 = 200 W / (m². ° C) the motor temperature is 84.63 ° C, below the search limit value.

Figure 6, is the graph constructed from the data generated for engine efficiency. Note how aluminum results are far superior to cast iron.

$$\eta_{motor} = \frac{Q_0}{h_2 \,.\, [A_L + (A_{Motor} - 32 \,.\, A_b)] \,.\, (T_b - T_\infty)} \quad 25$$

Another parameter to be analyzed is the effectiveness of the engine, which is the ratio between fin and non-fin motor heat exchange. The efficacy formulagiven by:

$$\varepsilon_{motor} = \frac{Q_0}{h_2 \,.\, A_{Motor} \,.\, (T_b - T_\infty)} \quad 26$$

Again, Figure 7, demonstrates that the results for aluminum are much higher than those obtained by cast iron.

Looking at Figure 7, we can conclude that a reasonable effectiveness value for a fin of 2.5 is achieved when h_2 is near 400 W / (m². ° C) for cast iron.

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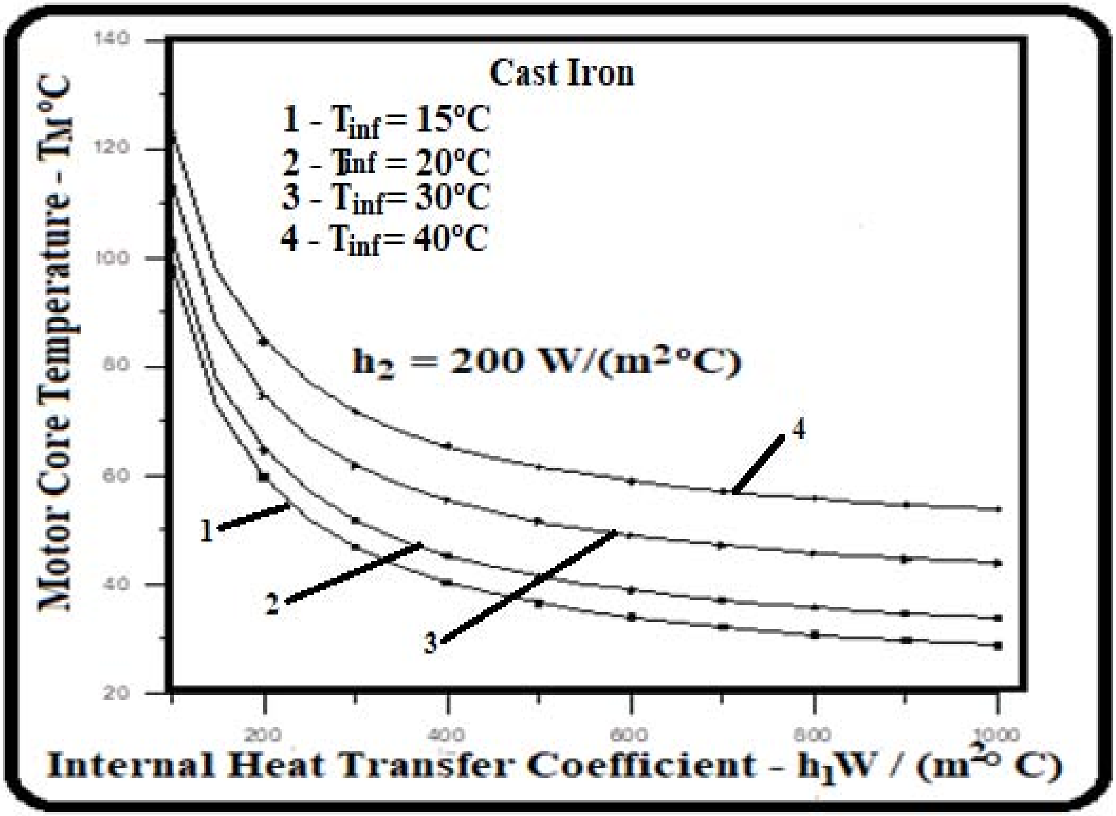

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Figure 5: Motor Core Temperature - h_1 x T_M

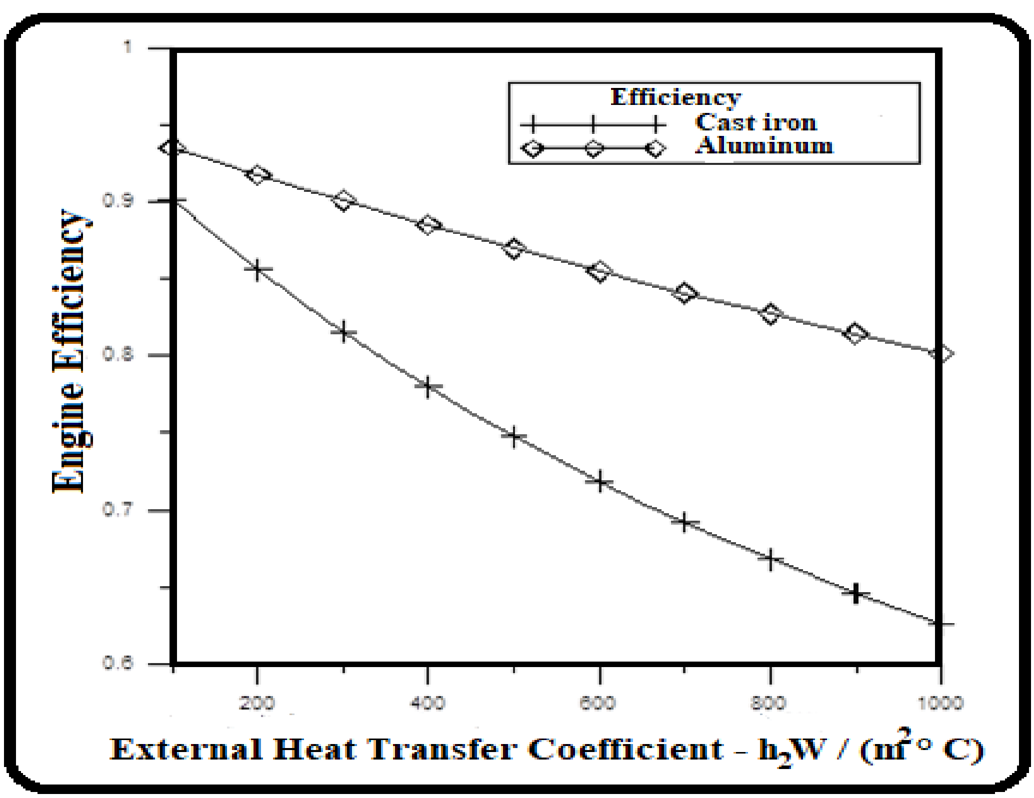

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Figure 6: Engine Efficiency

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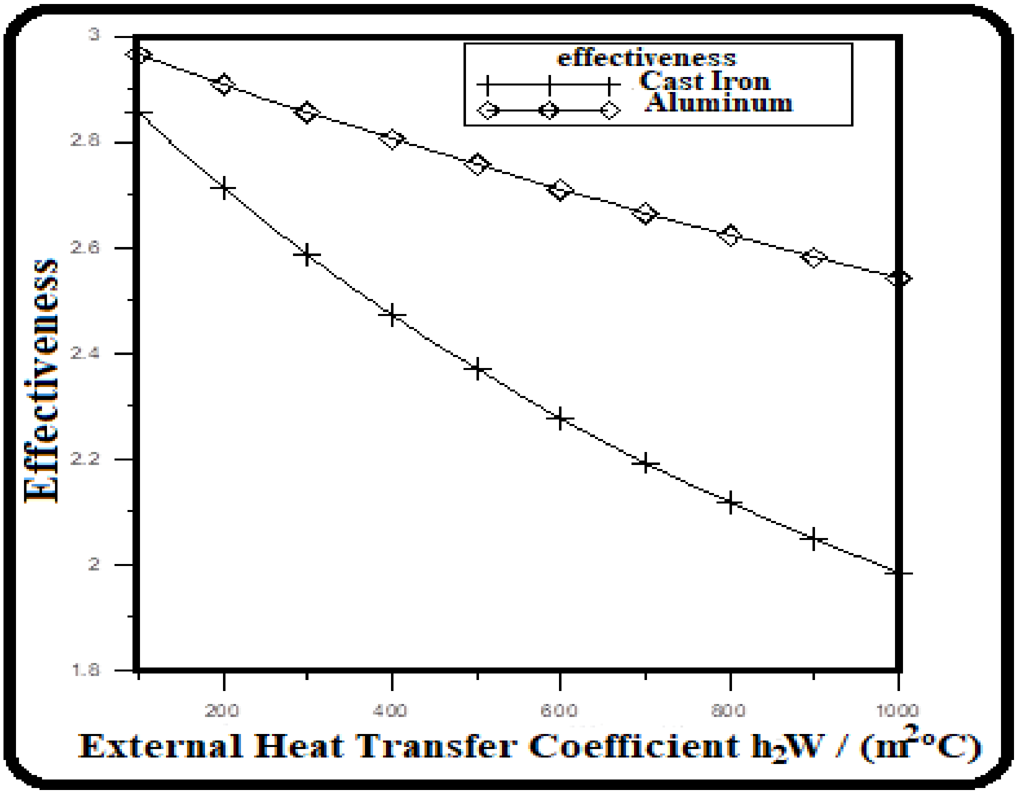

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Figure 7: Engine Effectiveness

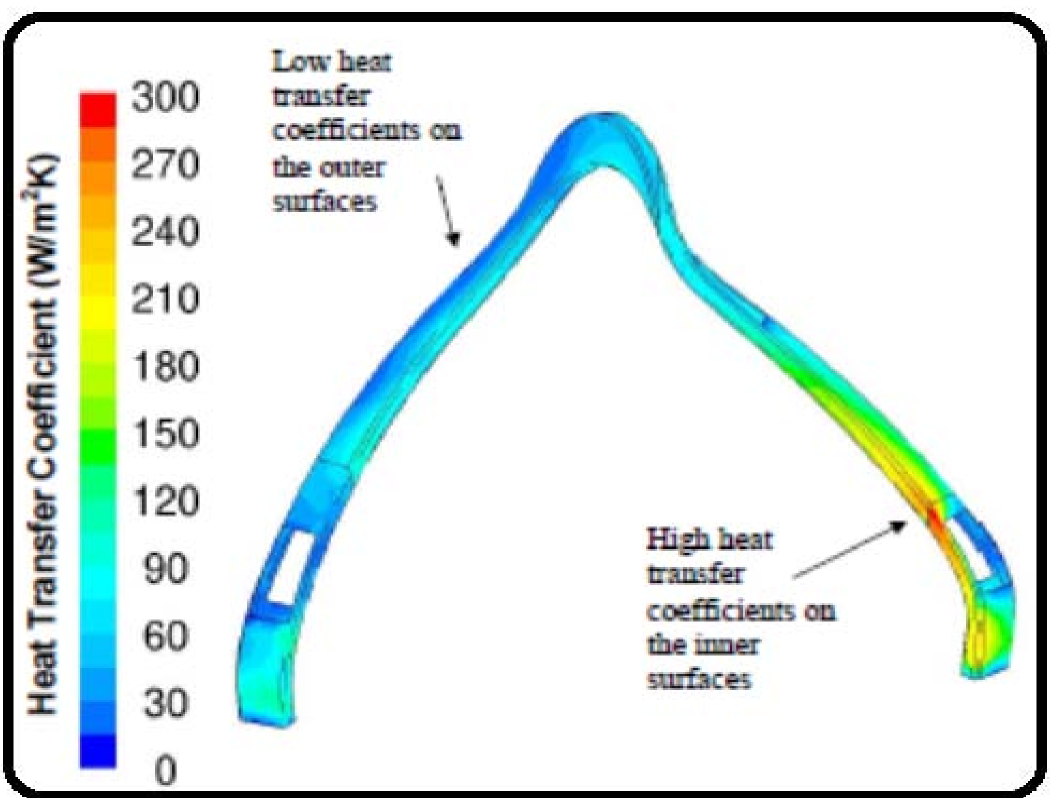

Figure 8: Contour for Local Heat Transfer Coefficient

Beng, Christopher Micallef(2006)

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Based on the results observed above, and in the graphs of efficiency and effectiveness, we conclude that for any values of $h_1 \geq 200$ W / (m². ° C) and $h_2 \geq 200$ W / (m². ° C) the engine temperature will have a satisfactory value. However, the values of h_1 and h_2 are physically limited. For h_1 to assume values greater than 400 W / (m². ° C), forced ventilation must be used with the aid of a fan inside the engine or by drilling holes in the housing to increase natural ventilation. In addition, for h_2 to assume values greater than 400 W / (m². ° C), ventilation must be increased in the environment where the engine is installed, which would generate more costs for the company.

The above results are consistent with the results presented and experimentally confirmed by Micallef (2006), Figure 8 above, in his doctoral dissertation entitled "*End Winding Cooling in Electric Machines*". In his studies, using experimental and numerical method CFD - Computation Fluid Dynamic, the author applied three distinct turbulence models, and the results showed that the closer to the motor core, the higher the heat transfer coefficient by convection acting on the internal surfaces.

The measured internal coefficient assumed values close to300 W / (m².K), a value that is included in the working range proposed by this study.

IV. Conclusion

The motor core temperature was computationally simulated by varying the internal (h_1) and external (h_2) convection heat transfer coefficients and the ambient temperature. The results demonstrated two things: the importance of the internal heat transfer coefficients and their physical limitations.

Regarding the heat transfer coefficients, we can conclude that the values of h_1 and h_2 cannot be treated separately. For very low h_1 and h_2 values the fins tend to be at the same temperature as the outside temperature, so there is no efficient heat exchange, overheating the engine. For very high h_1 values, which is physically impossible to obtain, we have that the fin base tends to stay with the motor core temperature, with is the usually conditions generally used by the one-dimension and two-dimension fin models.

We conclude that for any values of $h_1 \geq 200$ W / (m². ° C) and $h_2 \geq 200$ W / (m². ° C) the motor temperature will have a satisfactory value. However, as already mentioned, the values of h_1 and h_2 are physically limited. For h_1 to assume values greater than 400 W / (m². ° C), which is already a critical value to obtain for mechanical reasons, it is necessary to use forced ventilation inside the engine or drill holes in the housing to increase nature ventilation. The same reasoning can be used for the external coefficient h_2, which would entail a higher cost to the company, as it would be necessary to increase ventilation at the engine installation site.

Thus, the ranges, $200 \leq h_1 \leq 300$ and $200 \leq h_2 \leq 400$, are the limit values that guarantee the lowest value for the heat transfer rate required for efficient heat removal. Any values above these will increase the transfer rate and consequently decrease the motor core temperature, however, considering the difficulties of achieving these values in practical terms.

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