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Compressor Efficiency Improvement By Reducing Heat Transfer

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The Improvement of the Compressor Efficiency by Reducing Heat Transfer

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ABSTRACT

Many ways are possible to improve the compressor efficiency, like the reduction of the mechanical losses through valve or bearings which represent from 20% to 30% of total electric consumption power on the compressor. Another way is to decrease the pressure drop through the compression circuit of the compressor, which can reduce the temperature variation through the compressor…etc. In our case of study, we will be interested in the heat transfer and pressure drop through the suction circuit

In this paper, we will present the challenge done on the heat transfer reduction through the suction line of the CAJ4519Z compressors, in reducing from 10°C to 20°C the flow temperature through the suction line, and thus improve the cooling capacity by increasing density of the flow. Indeed, according to the mechanical conception of the compressor, the suction line and entering gas flow is in contact with the hot discharge line and flow through the cylinder head part. Thus, the thermal conduction phenomenon at this level heats up the suction gas and consequently the density of the refrigerant flow and compressor capacity is reduced.

In this case study, the cylinder head is cast iron material, and separates the suction line (flow at 64°C) and the discharge line (flow at 115°C) by a wall thickness of 0.8cm. . Consequently, the suction gas is warmed by the conductivity and increases the temperature between 10°C and 20°C depending on the operating condition. To reduce the conductivity phenomenon on the cylinder head part, a judicious material selection is done according to the Ashby methodology based on the conductivity coefficient, and a new concept of cylinder head is done. Before testing the new concept, CFD (Computational Fluid Dynamics) simulation calculates the improvement from the existing to the new cylinder head concept, and allows defining the position of the sensors. The laboratory test results confirm the simulation results.

Thus, thanks to the thermal characteristic of the material and re design the cylinder head part, we can reduce the temperature and improve by 2% (average value) the cooling capacity of the compressor.

1. INTRODUCTION

Today, improving the efficiency of the compressor is an ongoing challenge for engineers in order to find new concepts to respond to customer application and specifications needs Many techniques are possible for the enhancement of the compressor efficiency; however the most important thing is to know and identify the significant factors which have strong effect on the efficiency of the compressor. Thus, based on the COP definition (Coefficient of Performances), we notice that there are two factors defining the efficiency:

- The power consumption of the compressor (Wabs: Motor characteristics, operating condition and mechanical losses through the compressor).
- The cooling capacity (Qpf: Thermodynamic characteristics of the flow through the compressor)

The power consumption is linked by the mechanical losses, thermal losses and also the operating condition (mass flow, temperature) through the compressor according to the equations below:

$$P_u = \eta_{ele} \times P_{abs} \quad (1)$$

$$P_u = C_u \times \omega \quad (2)$$

With :

$$\omega = 2 \times \pi \times f \quad (3)$$

Then :

$$C_u = \frac{P_u}{2 \times \pi \times f} \quad (4)$$

With :

$$\eta_{eff} = \frac{W_{is}}{P_u} = \frac{m(h_{21is} - h_{12})}{P_u} \quad (5)$$

$$C_u = \frac{m(h_{21is} - h_{12})}{2 \times \pi \times f \times \eta_{eff}} \quad (6)$$

$$P_{abs} = \frac{m(h_{21is} - h_{12})}{\eta_{eff} \times \eta_{ele}} \quad (7)$$

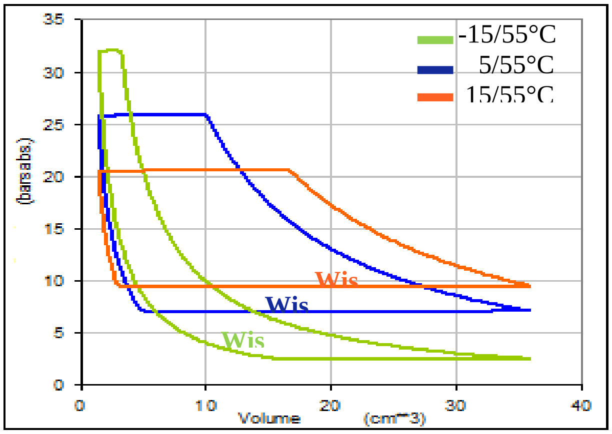


Figure 1: P-V diagram according operating condition

The other parameter defining the COP factor is the cooling capacity: Qpf, which is defined according the following equations:
According to the 1st law of thermodynamics applied to the compressor in steady state condition, and considering that the variation of the kinetic energy and potential energy are neglected according to the heat quantity and external energy exchanged, then we obtain:

$$\Delta U = \Sigma W + \Sigma Q \quad (8)$$

$$\Delta U = P_{abs} + \dot{m}(h_1 - h_2) + Q_a \quad (9)$$

in steaty state condition :

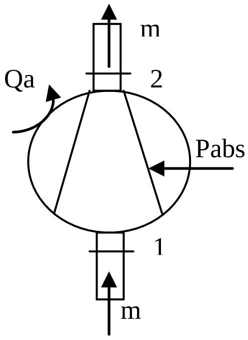
$$\Delta U = 0$$

So we obtain :

$$P_{abs} = \dot{m}(h_2 - h_1) - Q_a \quad (10)$$

with :

$$Qpf = \dot{m}(h_2 - h_1)$$



Thus, we can conclude that a significant important parameter for the enhancement of the compressor efficiency is: the mass flow of the refrigerant through the compressor. The mass flow of refrigerant can be defined according to the volume flow and the density. The volume flow of the refrigerant through the compressor is defined by the compressor design; whereas the density depends of the temperature through the system (see Figure below).

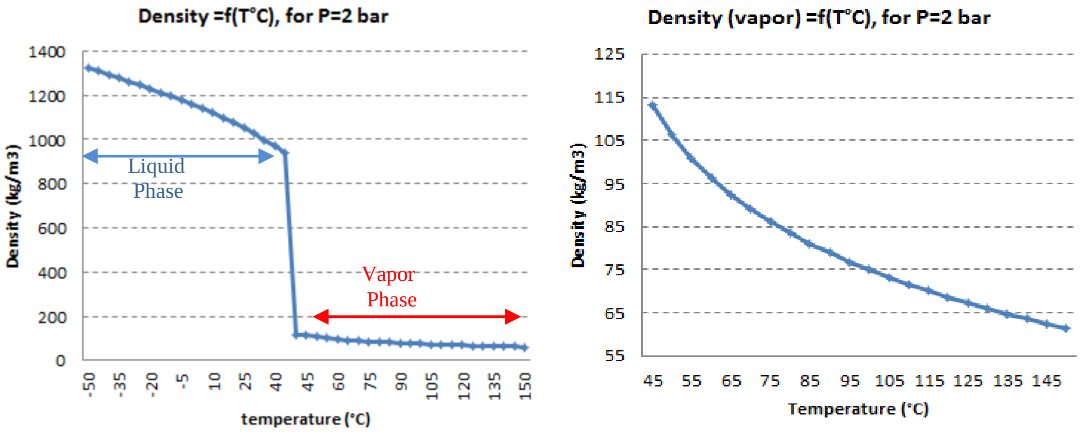


Figure 2: Density evolution according the temperature for R404A

The density is sensitive to the temperature variation, therefore if the temperature would be decreased by 10°C, the vapor density could be increased by 8% (average value).So, if it is possible to reduce the temperature or the heat exchange phenomena through the compressor we would expect an enhancement of the efficiency of the compressor. To identify the thermal behavior on the compressor system, a thermal mapping is realized in order to define which parts of the compressor system could be changed to improve the efficiency on the system. On the chart below, we can see the temperature evolution of the flow through the compressor from input to output of the system according to several operating conditions. We have judiciously placed the sensors through the suction and discharge line of the system in order to understand where, when and why the flow warms up in the compressor (see the results on the below figures).

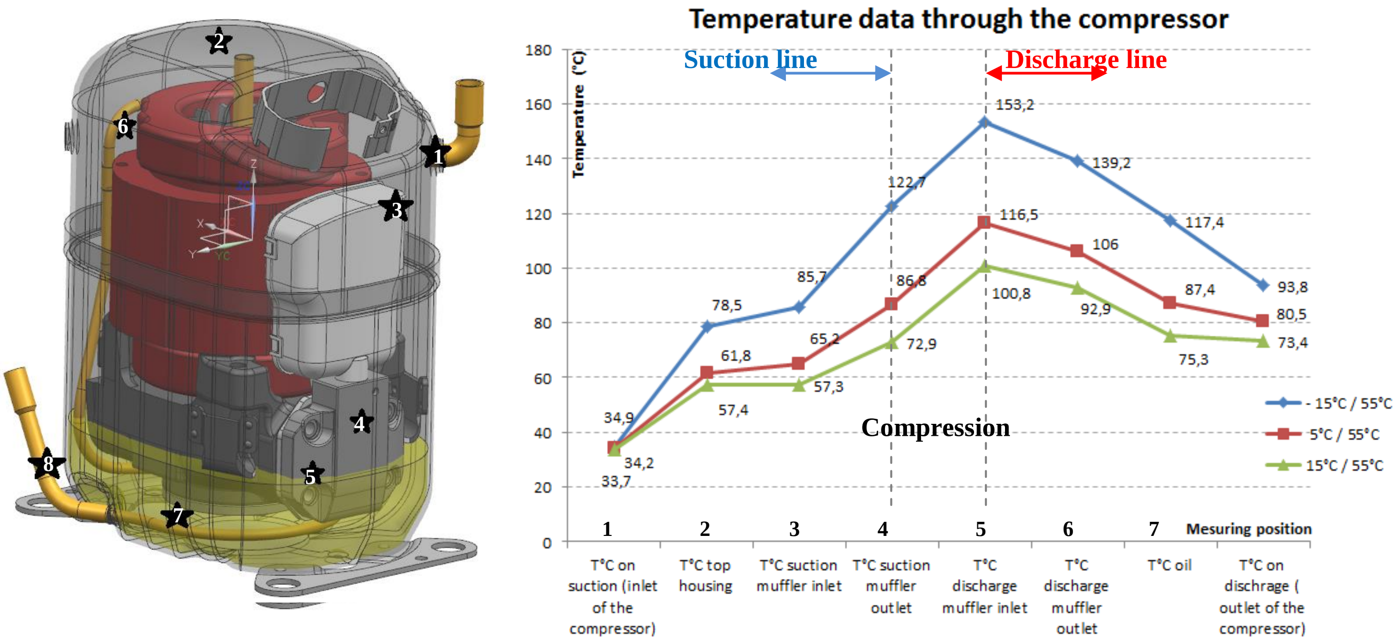


Figure 3: Thermal mapping for compressor CAJ4519Z

Thus, on this thermal mapping we can identify two areas where the flow sustains a heat exchange:

-The suction line: +51°C from the inlet of the compressor to outlet of the suction muffler (at 5/55°C)

-The discharge line: -36°C from the inlet of the discharge muffler to outlet of the compressor (at 5/55°C)

The only useful part of the compressor is the compression part, therefore all thermal phenomena before or after the compression could be modified to enhance the efficiency of the compressor.

When we analyze this thermal mapping, and more precisely the difference of temperature through the suction and the discharge mufflers, we notice that the higher temperature gap is located on the suction muffler. Indeed, we have 20°C (average value) difference through the suction muffler for 10°C (average value) through discharge muffler. In addition, the suction muffler for this compressor is composed by two different materials: Thermoplastic and Cast Iron. The beginning of the muffler is thermoplastic material and the end is cast iron which is nearest to the hot area of the compression. That is why, we observe a higher temperature difference through the suction muffler: because of the materials characteristics of the cast iron.

The two-material composition of the suction muffler can be explained by the limited level of the thermal properties of the thermoplastic material. Indeed, thermal characteristics of thermoplastics are not easily applicable on strong thermal operating conditions because of thermal attributes such as: maximum service temperature (T maxi), glass temperature (Tg), thermal conductivity (λ) or thermal expansion coefficient (α). These characteristics are lower than the metal and alloy materials commonly used for mechanical systems.

Engineers are often conservative in their choices, reluctant to consider new materials with which they are unfamiliar, and with good reason. Data for the existing conventional materials are established, reliable and easily found. Data for the newer emerging materials may be incomplete or untrustworthy. However, the materials world changes constantly, and new thermoplastics with good thermal properties appear and can replace metallic parts in mechanisms. Thus, in the following, we explain how to select the best materials for the suction muffler, in replacing the cast iron part of the cylinder head by thermoplastic materials and by using a material choice methodology established by Dr. Ashby in order to reduce the temperature gap through the suction part of the compressor.

2. BEST MATERIAL TO REDUCE HEAT CONDUCTIVITY

The best practice on the material selection for mechanical design is to integrate the interaction between function, material properties, process and the shape upstream of the conception of the system. To use the methodology of materials selections established by Dr. Ashby, it is necessary to define the minimum information like the function, objective and constraints of the system. Indeed, it is necessary to translate the constraint according to the part function which will be linked by a combination of materials properties, called “Performance Index”.

A- Ashby methodology approach for suction muffler application

The Dr. Ashby methodology for material selection is mainly tackled in four steps:

1- *Translation:* re-interpreting the design requirements in terms of function, constraints, objectives, and free variables.
2- *Screening:* deriving attribute limits from the constraints and applying these to isolate a subset of viable materials.
3- *Ranking:* ordering the viable candidates by the value of a material index, the criteria of excellence that maximizes or minimizes some measure of performance.
4- *Documentation:* seeking documentation for the top ranked candidates, exploring aspects of their history, their established uses, their behavior in relevant environments, their availability, and more, until a sufficiently detailed provides the final choice.

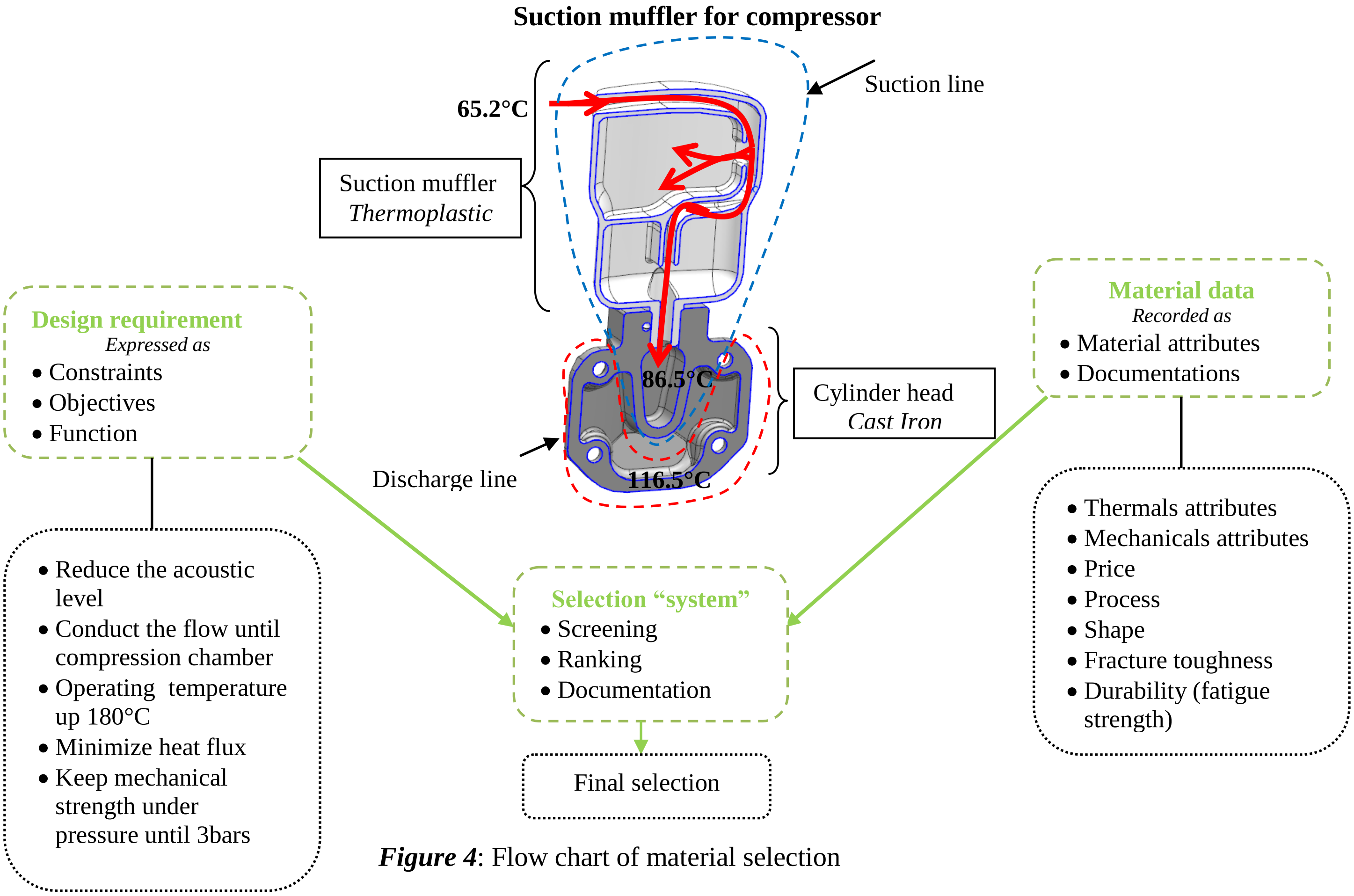


Figure 4: Flow chart of material selection

The suction muffler function is to drive the gas flow from the compressor inlet to the compression chamber by decreasing the acoustic level. The suction gas flow across the muffler until warms up as it approaches the inlet of the compression chamber. The key element of this case study is to add the heat insulation function on the main function of suction muffler. The following table provides the requirements for selecting the best suction muffler material to optimize the heat insulation function:

Design requirement for suction muffler with heat insulation function	
Function	To guide the gas flow from inlet to the compression chamber
Objective	Minimize the heat flow per unit mass (minimum mass exchanger)
Constraint	Support pressure differential Operating condition up to 180°C Modest cost Glass temperature up to 180°C Injection molding process Thermoplastic family Insulating
Free variable	Wall thickness Choice of material

B- Translation of requirements by performance index and the choice

More than 900 grades of polymer exist, and to know which is the better for our system, we will translate the constraint of the design requirement to answer the objective according to the function of the system. On the suction muffler there are convection and conduction phenomena between the material and the gas flow. The heat flow through the suction muffler and the discharge muffler is done by thermal conduction. According to the Fourier's law the heat transfer by conductivity, is defined by the following mathematical expression, on steady state condition:

$$Q = \frac{\lambda}{e} \cdot \Delta T \qquad (11)$$

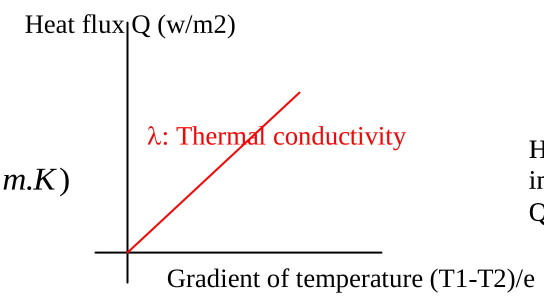
$with:$

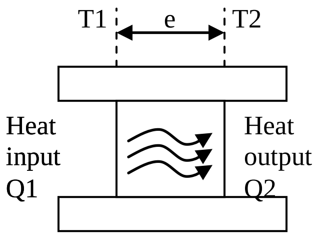
$Q : heatflux\,(W/m^2)$

$\lambda : thermal\ conductivity\,(W/m.K)$

$e : thickness\ wall\,(m)$

$\Delta T : temperature\ (K)$





Another constraint is that the wall thickness must be sufficient to support the pressure ΔP between the suction and discharge. This requires that the stress in the wall remain below the elastic limit, σy. The mathematical expression link the constraint by the design is defined like following expression:

$$\sigma = \Delta P \cdot \frac{R}{e} < \sigma_y \qquad (12)$$

$with$

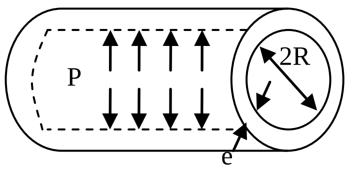
$\Delta P : Pressure(Pa)$

$R : radius(m)$

$e : Thickness(m)$

$\sigma : stress(MPa)$

$\sigma_y = Yield\ strength\quad (MPa)$



The free variable "e", the thickness of the wall, could be eliminated from both equation (11) and (12), and gives the following expression:

$$\left.\begin{aligned} e &= \lambda \cdot \frac{\Delta T}{Q} \\ e &= \frac{1}{\sigma_y} \cdot \Delta P \cdot R \end{aligned}\right\} \quad Q = (\lambda \cdot \sigma_y) \cdot \left(\frac{\Delta T}{\Delta P}\right) \cdot \left(\frac{1}{R}\right) \qquad (11)(12)$$

At this stage of methodology, we just define the constraint according to the function that the muffler must realize. Now, we will establish this equation for the objective to minimize the heat flow per unit of mass. So, it is necessary to reduce the ratio Q/m, and obtains following expression:

$$\frac{Q}{m} = \frac{(\lambda \cdot \sigma_y^2)}{\rho} \cdot \left(\frac{\Delta T}{\Delta P}\right) \cdot \left(\frac{1}{R \cdot V}\right) \qquad (13)$$

$$\begin{aligned} & with: \\ & m : masse(kg) \\ & V : volum(m3) \\ & re\min der: \\ & m = \rho \cdot V \end{aligned}$$

Notice: the strength σy is now raised to power of 2 because the weight depends on wall thickness as well as density, and wall thickness varies as 1/σy.
On the equation above (13), we can identify three parts, like following:

$$\frac{Q}{m} = \underset{\text{1st}}{\boxed{\frac{(\lambda \cdot \sigma_y^2)}{\rho}}} \cdot \underset{\text{2nd}}{\boxed{\left(\frac{\Delta T}{\Delta P}\right)}} \cdot \underset{\text{3rd}}{\boxed{\left(\frac{1}{R \cdot V}\right)}} \qquad (13)$$

- The 1st one, is a combination of the material properties attributes called "performance index"
- The 2nd one, defines the condition
- The 3rd, is a design parameter of the system

Thus, thanks to the equation (13), we can define the index of performance to select the best material to satisfy the function, the objective, and the constraint for the muffler. Similarly, it is also possible to define the cheaper material for this application introducing the relation between the mass and the price, like following expression:

$$\begin{aligned} & \Pr ice = m \cdot Cm \qquad (14) \\ & with \\ & Cm : price / kg \\ & Thus, we\ obtain \end{aligned}$$

$$\frac{Q}{m \cdot Cm} = \boxed{\frac{(\lambda \cdot \sigma_y^2)}{\rho \cdot Cm}} \cdot \boxed{\left(\frac{\Delta T}{\Delta P}\right)} \cdot \boxed{\left(\frac{1}{R \cdot V}\right)} \qquad (15)$$

After to have defined the performance index of the new suction muffler, along with insulation heat function and the acoustic criteri;, the last step of the methodology is to choose the material thanks to the material chart below:

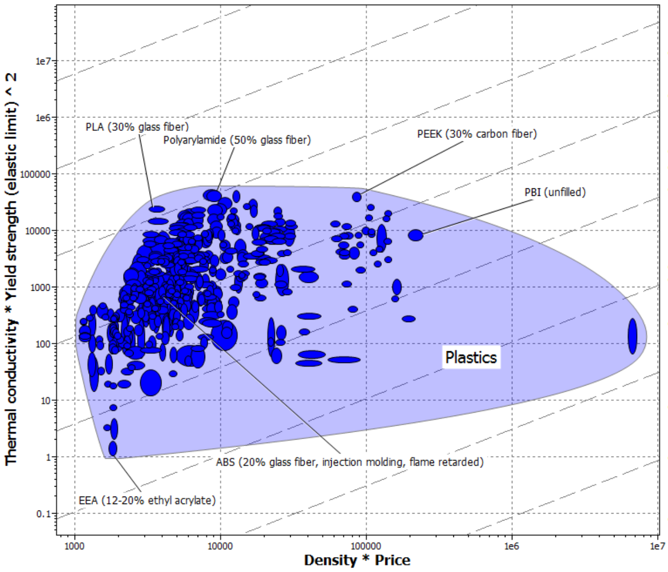


Figure 5: Material properties chart

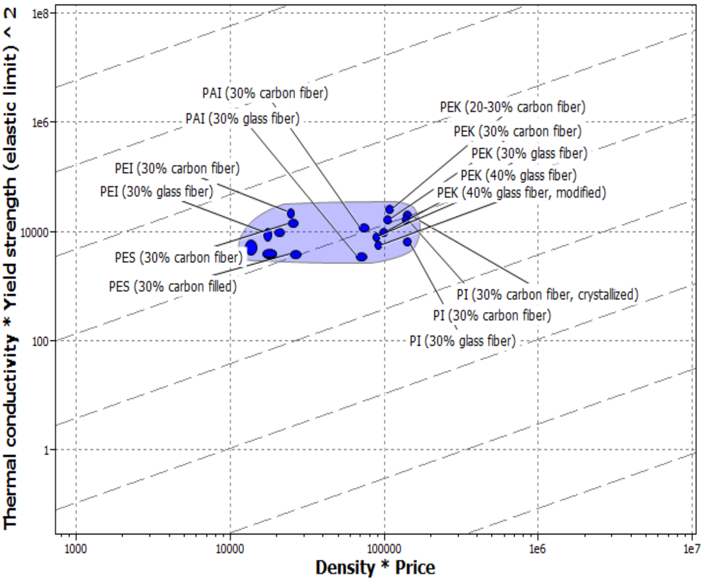


Figure 6: chart of material properties adding constraints

On the figure 5, we take all Thermoplastics grades according to the performance index defined above. There are more than 900 thermoplastics grades, and it is difficult to test all. Thus, we have added material characteristics, like maximum service temperature (>180°C), glass temperature (>180°C), Young's modulus (>10GPa), a satisfactory chemical resistance and so on. Therefore, we obtain only 18 thermoplastics grades which correspond at the demand criteria (see 2nd figure).

According to the objective of the new suction muffler, it is necessary to minimize the performance index, therefore the best material candidate must be located at the top left of the figures. Thanks to these material charts of materials properties we can identify 5 families of thermoplastic which are applicable for new muffler: PES, PEI, PAI, PEK and PI. From this group, we can delete the PES (bad resistance to chemical solvents whereas thermal properties are interesting), and the PEK & PI (too expensive). The PEI 30% Carbon Fiber/Glass Fiber and PAI 30% Carbon Fiber/Glass Fiber would be a good choice for the new muffler, based on the table below:

	PEI 30%GF	PEI 30%CF	PAI 30%GF	PAI 30%CF
Prix (€/kg)	11-12	16-18	40	40
E (GPa)	9-11	18-22	10-11	21-23
σy (MPa)	161-177	160-190	90-110	140-180
T°maxi. Service (°C)	200	200	200-220	200-220
Glass T° (°C)	205-230	205-230	270-280	270-290
λ (W/m.°C)	0.2-0.4	0.7-0.8	0.3-0.4	0.5

Table 1: Main characteristics of applicable materials

In conclusion, thanks to this methodology we are able to identify among more than 900 thermoplastics grades, the best materials which can correspond at our application, without be an expert on material. This methodology of material choice can be used for all kinds of system to define from the beginning of a new system conception, the best material corresponding to the needs. On the following parts of this study, we validate the choice and the concept by simulation and laboratory test in order to verify the enhancement of the cooling efficiency of the compressor with the new material.

3. VALIDATION BY SIMULATION AND TEST : THE HEAT EXCHANGE

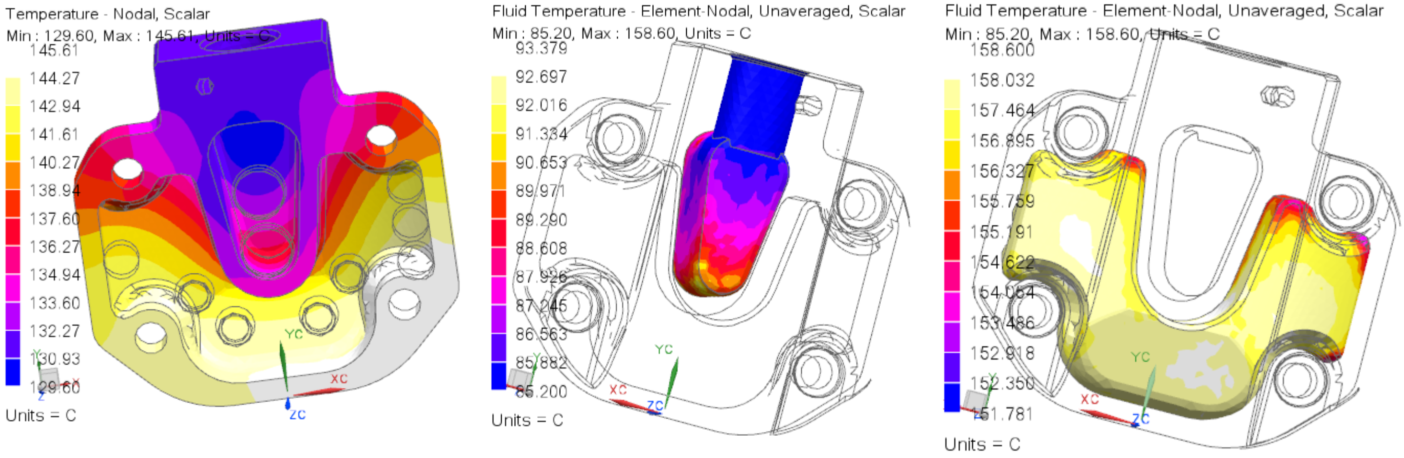
The definition of the heat flux area and the potential material for the new application to improve the efficiency of the compressor must be validated by simulation before prototyping. Therefore, we do simulation study of the existing model and the new model of the muffler, in order to estimate the benefit on the heat exchange through the suction muffler.

A- Simulation model and results

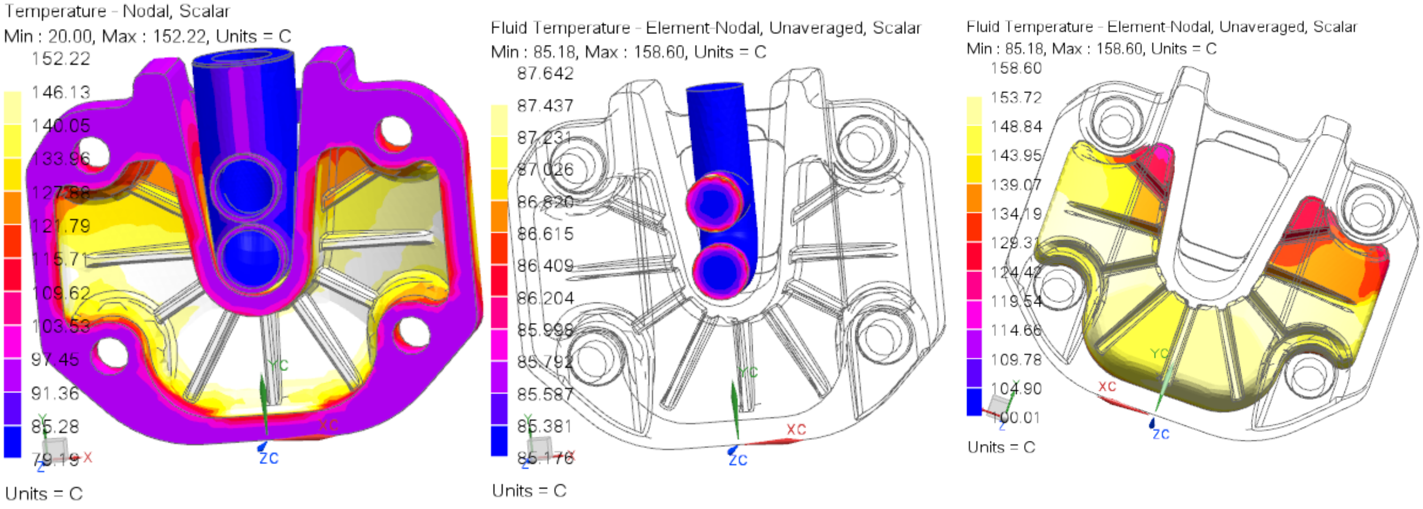
For simulation, we analyzed the cylinder head portion of the suction muffler, where the gas flow heats up. The simulation model is based on the -15/55°C operating condition (which has higher ΔT), according the following boundary conditions:

- Operating conditions: -15/55°C
- Mass flow: 0.017kg/s
- Flow temperature at suction: 85.2°C
- Suction pressure: 3.6bars
- Flow temperature at discharge: 158.3°C
- Discharge pressure: 25.4bars
- Flow ID: R404A
- Thermal conductivity coefficient

<u>The simulation result for current design:</u>



<u>The simulation result for new design with the new material:</u>



On the simulation results we notice a difference in the temperature at the end of the suction muffler between current design and the new design. Indeed, on the current design we have a ΔT=8°C whereas on the new design we have a ΔT=2°C. Thus, we achieved a reduction of 6°C on the temperature of the flow, and improve the cooling capacity of the compressor by 4% than the current design.

B- Test result and comparison

The following step of the validation of the concept is the laboratory test with a prototype of the new concept in order to validate the idea of the enhancement of the compressor efficiency by reducing the heat flow.
Based on the simulation analysis, the sensors are placed through the suction line, more precisely at the end of the suction muffler in order to make comparison with the thermal mapping with the current design. Thus we obtained the following results on the temperature parameter:

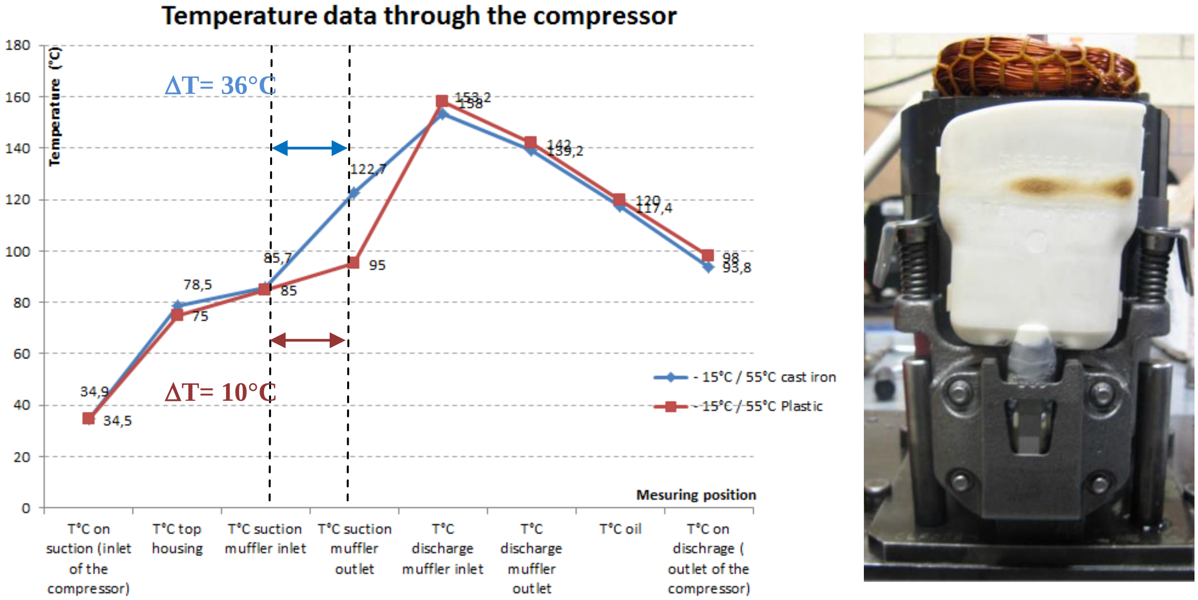


Figure 6: Thermal mapping comparison for compressor CAJ4519Z

On this thermal mapping we notice a temperature reduction through the suction line. Nevertheless, the temperature of the outlet of suction muffler for current design has not been taken, exactly at the same level than the new design, that why we notice a higher ΔT on the thermal mapping. Thus, thanks to the simulation, we can define more precisely the evolution of the temperature at the end of the muffler whereas the laboratory test will be difficult sometimes to do measurement with precision. In addition, when we compare the Qpf between the current design and the new design of the suction muffler we notice an enhancement of 3.2% (for operating condition at -15/55°C).

Thus, we can conclude that the thermal effect could be a valuable change in order to improve the efficiency. However, when we analyze the COP factor of the compressor, we do not find the same evolution of the Qpf factor. Indeed, the Wabs parameter is degraded according to the mass flow and we improve only the COP by 1% or 2% according to the operating condition.

4. CONCLUSION

To conclude on this study, we can say that the thermal effect in the compressor system is sensitive to both the cooling capacity and the COP factor. Therefore if we want to significantly improve the efficiency of the compressor the thermal aspect alone is not sufficient. Other parameters like mechanical losses (lubrication), motor (torque and thermal losses), and pressure losses through the compressor (acoustics, and power consumption) impact the COP factor. Thus, the improvement for only on one of these phenomena couldn't be sufficient.
This paper has demonstrated that new approaches for material selection, at the beginning of a new concept, can be accomplished with minimal expertise. This approach can lead the engineer through the feasibility of innovating on the choice of new material.
The following step of the study is to realize a complete compressor model with all physical phenomena in order to improve the COP factor and show the limit of the compressor system.

NOMENCLATURE

Pabs	total electric consumption	(W)	U	energy	(W)
Pu	useful electric consumption	(W)	e	wall thickness	(m)
ηele	electric efficiency	(-)	ΔT	differential of temperature	(°C)
ηeff	effective efficiency	(-)	λ	thermal conductivity	(W/m.K)
Cu	useful torque	(N/m)	ΔP	differential of pressure	(Pa)
ω	velocity	(rad/s)	R	radius	(m)
f	frequency	(Hz)	σ	stress	(MPa)
Wu	useful power	(W)	σy	yield strength	(MPa)
m	mass flow	(kg/s)	m	mass	(kg)
h	enthalpy	(kJ/kg)	V	volume	(m3)
Q	thermal flux	(W)	Cm	price/kg	(€/kg)
Qa	thermal convective power	(W)			
Qpf	cooling capacity	(W)			

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