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Influence of inter-coolers technologies on the performance of isotherm centrifugal compressors

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ABSTRACT

It is well known that gas compressor work can be greatly reduced by inter-stage cooling. Since decades, isotherm compressors are commonly used where very large volume of gases is needed and low power consumption is necessary, so that the efficiency of the industrial process is greatly improved. The use of large amount of compressed air, oxygen or other gases is very common in different industrial sectors like air separation, petrochemical plants, mining, steel industries as well as preparation of synthetic natural gas.

The main optimization goals in compressors technology are focused either on rotating components (mainly stage aerodynamics) as well as on intercooling (or heat exchange) process. In particular, current development is aiming either on improvement of cooling efficiency or (keeping the same efficiency) on size reduction, which is directly related also to overall cost reduction. Such improvements can derive from the use of different materials, coolers type/methods, geometries, manufacturing technologies, fouling modelisation and prevention etc. In this paper, a comprehensive and quantitative analysis of the influence of different intercoolers aspects is carried out with the aim to isolate the most critical factors to achieve an optimal combination between capital and operative costs of isothermal compressors.

INTRODUCTION

Isothermal compressor has been an "old dream" of engineers where an attempt to drastically reduce the shaft power consumption is pursued. An ideal isotherm compressor of course cannot be built (it requires infinite compression and intercooling stages), however since more than 100 years "approximations" with adiabatic (radial) stages alternating with intercoolers are widely used in several industrial areas. Main air compressors (MAC) and booster air compressors (BAC) for example are used in air separation plants (ASU) and for CO_2 and N_2 applications. In ASU industry, the compression process is responsible for more than 60% of the total power required by the plant. Therefore the isotherm compression is a very attractive solution since it saves significant power when compared with "standard" adiabatic compressors.

In the last century different technical solutions have been applied in order to optimize the inter-stage cooling process, however, nowadays in the market there are mainly 2 different types of these compressors: Inline compressors (with integrated coolers) and geared-type compressors (with external coolers). Both types operate normally at constant speed, are driven by an electric motor or steam turbine and use inlet guide vanes (IGVs) for regulating the process gas flow. Figure 1 shows these 2 compressor types.

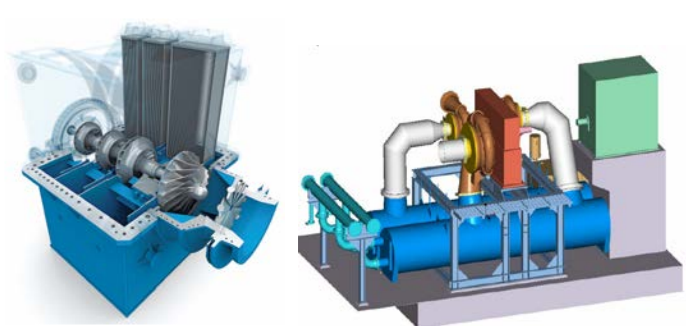

Figure 1: Typical MAC inline isotherm compressor (a) and BAC gear-type compressor (b)

In both type of isotherm compressors, the intercooling process plays an important role and has a great impact on the compression performance, design, maintenance and overall capital and running costs. The power saving, when compared with adiabatic compression, increases when the pressure ration increases, thus the intercooling process is more and more beneficial for high pressure ration compressors.

There is a continuous effort to optimize the cooling process and consequently the compressor performances. Table 1 summarize the effect of a reduction of 1%, 2% and 5% on the heat transfer for the intercoolers #1 and #2 in a 3-stage inline isotherm compressor with a low pressure ration equal to 6.

Table 1: Effect of heat transfer reduction on the intercooling process on the total power for small, large and medium inline isotherm compressors

ΔQ		Small		Medium		Large		Average		
		1.IC	2. IC	1.IC	2. IC	1.IC	2. IC	1. IC	2. IC	Total
-1%	ΔT [°C]	0.3	0.71	0.3	0.75	0.32	0.79	0.31	0.75	
	ΔPower [-]	0.14%		0.12%		0.13%				+0.13%
-2%	ΔT [°C]	0.61	1.47	0.65	1.55	0.64	1.54	0.63	1.52	
	ΔPower [-]	0.26%		0.25%		0.26%				+0.26%
-5%	ΔT [°C]	1.52	3.38	1.62	3.73	1.58	3.67	1.57	3.59	
	ΔPower [-]	0.61%		0.62%		0.63%				+0.62%

The calculation is done taking into account a small, medium and large flow compressor. The analysis shows that a reduction of 5% in heat transfer corresponds a penalty of about 0.6% on the total shaft power. Such penalty in MAC (Main Air Compressor) used for ASU is considered very significant. It is worth to note that in higher pressure ration compressors (i.e. booster compressors), the effect of heat transfer reduction is much higher.

Gas pressure losses occurring on the intercoolers have also an effect on the shaft power, but the influence is much lower than the heat transfer, typically one order of magnitude. Also, both heat transfer and pressure losses parameters are strong depending on geometry factors, size, materials etc. Therefore it is often challenging to optimize performances vs. reliability and evaluate costs vs. benefits.

COOLER DESIGN

In the last 30 years of isotherm compressors history, three different types of coolers were developed: Finned/tube coolers, plate fin/tube coolers and so called “High Performance” plate fin/tube coolers. The latter can be considered an improvement of the typical plate fin/tube arrangement.

Finned/tube coolers (schematic in Figure 2) were very common for isotherm compressors until about 20 years ago and they are designed using tubes of, normally, large diameter (>20mm) surrounded by a number of circular or squared fins. The contact between tubes and fins is guaranteed by means of tight mechanical (press) fit, tension winding, adhesive bonding, soldering, brazing, welding, or extrusion. The typical fin densities for flat fins vary from 250 to 800 fins/m and fin thicknesses vary from 0.08 to 0.25 mm.

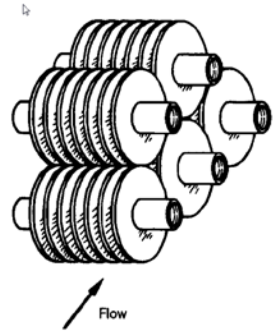

Figure 2: Finned/tube heat exchanger schematic

These exchangers are extensively used as condensers and evaporators in air-conditioning and refrigeration applications, as condensers in electric power plants, as oil coolers in propulsive power plants, and as air-cooled exchangers (also referred to as a fin-fan exchanger) in process and power industries. Finned-tube exchangers are more rugged and practical than plate fin/tube exchangers however also more expensive on a unit heat transfer surface area basis. Today they are almost never used anymore in isotherm compressor.

The plate fin/tube coolers represent nowadays a standard solution for many business areas such as petrochemicals, power generation, process and other industries. The design consists in a package of fins which are crossed by a number of tubes where the coolant media is flowing (Figure 3). There is therefore a heat exchange between the tubes, the fins and the outer gas. Typical cooling media is water with or without additives, depending on site conditions.

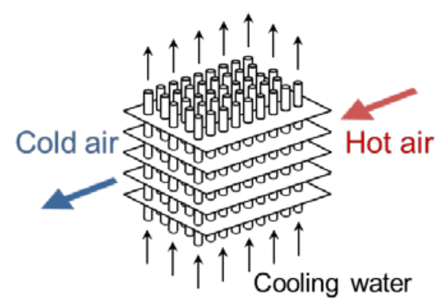

Figure 3: Typical plate tube/fins cooler arrangement

The optimal contact between tubes and fins is of primary importance because it affects significantly the heat transfer between the cooling media and the fins. Several technologies are used to guarantee the optimal contact between tubes and fins but typically the tubes are expanded by means of an expansion tool (sphere or bullet) so the fins around the tube diameter are deformed and ensure the best contact between the two surfaces. Nowadays, the competitiveness of the market and hence the continuous improvement of efficiency of industrial processes require a number of severe specifications for these fin/tube heat exchangers such compactness, thermal performances, geometrical layout, material resistance and, at the end, capital and operational costs. Standard material used for fin/tube coolers is Copper-alloy for the tubes with aluminium or copper for the fins. Copper-alloy tubes, e.g. CuNi10Fe, ensure best heat transfer and are very suitable for most applications. In cases where very high chlorides concentration is present (see water for example), CuNi30 is an excellent choice. Near ammonia plants, copper and copper alloys are not normally used and other materials are selected, for example Stainless Steel in combination with coated fins.

Standard plate fin/tube coolers

Great attention is focused on the optimal configuration between tube diameter, fin thickness, fin pitch and tubes arrangement. The use of "turbulators" in the fins in order to promote vortex generation is also quite common [5, 6, 7 and 8]. In this case different solutions are implied as winglets, recesses, louvers etc. All such devices increase the heat transfer however they also increase the pressure losses on the gas side, which obviously has a negative effect on the whole process downstream the cooler.

To find the optimal arrangement of these parameters a lot of literature is focused on detailed numerical analysis of different geometrical configurations [3,4]. Accurate analysis is of heat transfer prediction by means of CFD is often very challenging because is very much dependant on the turbulence model used and the quality of the computational mesh in the boundary layer regions. The work of Bergamasco et al. [2] shows that in the specific analysed geometrical configuration the normalized friction factor defined by the Darcy-Weisbach eq. 1):

$$f = \frac{2\Delta p \cdot D_H}{L \cdot \rho \cdot u} \qquad 1)$$

decreases as the Reynolds number increases and the heat transfer coefficient increases (Figure 4). The trend of the friction factor is consistent with that of a *Moody diagram* for a turbulent flow and constant relative wall roughness (eq. 2).

$$h = \frac{\phi}{S \cdot \Delta T} = \frac{\phi}{S \cdot (T - T_W)} \qquad 2)$$

In parallel with the numerical analysis, an experimental campaign was carried out together with the cooler supplier to assess the cooler bundle performances [11].

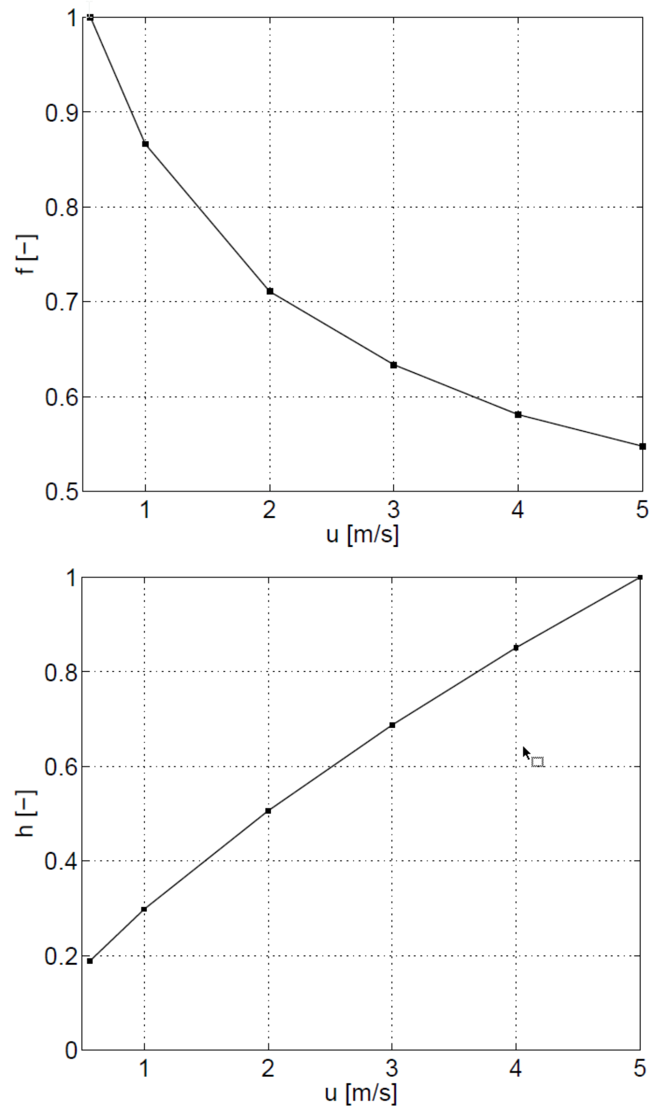

Figure 4 Normalized friction coefficient (a) and heat transfer coefficient (b) as a function of flow velocity [2]

The goal of the measurement was to validate the design and the prediction tool which are used in the definition of the isotherm compressor layout. The experimental arrangement consists on a tube/fins cooler bundle module implemented in a wind tunnel which can match various flow conditions. The experimental facility consists in an open loop circuit where the air is sucked from the ambient with a centrifugal fan. Afterwards the air is pushed in duct where is pre-heated in order to reach the desired inlet temperature on the test section (Figure 5). Before reaching the test section, the air goes through 3 different flow conditioners to achieve uniform velocity and temperature. The cooler bundle module in the test section has exactly the same dimension of the "real" bundle used in the isotherm compressor (Figure 6). The only difference is the overall length of the bundle. The wind tunnel is equipped with several instruments for measuring pressure, temperature, water flow, air flow etc. Data were acquired after about 50 minutes of waiting time for each experiment, so that constant thermal conditions were achieved.

Figure 7 shows the comparison between the measured heat transfer and the prediction using the standard Aspen/HTFS heat transfer software ([15]). The difference between measurement and prediction is basically equal to zero, therefore the measured data fully validated the cooler design in terms of heat transfer.

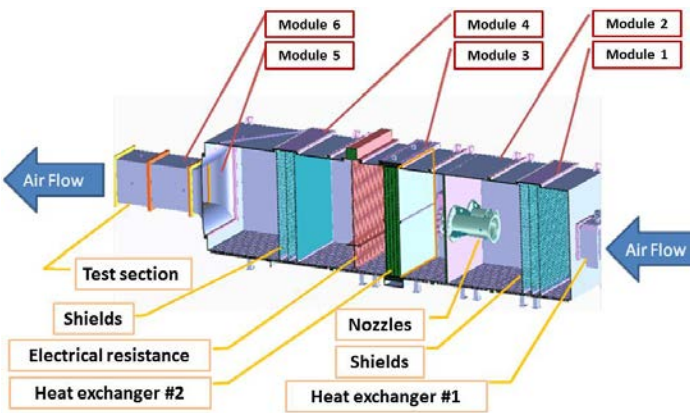

Figure 5: Experimental test rig for cooler bundle performance test

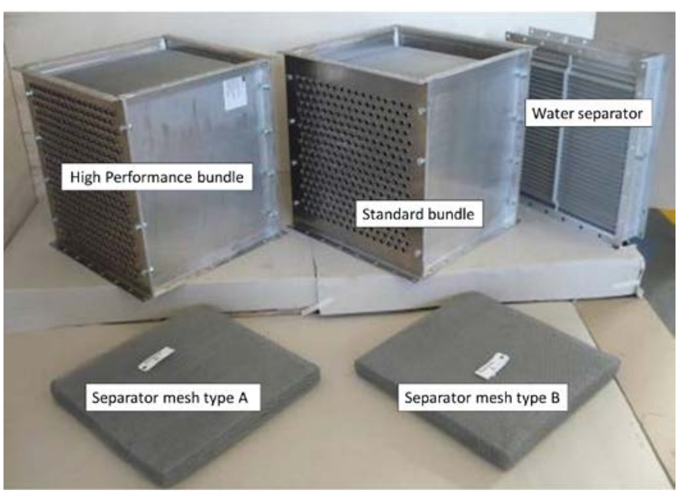

Figure 6: Investigated cooler bundle samples, water separator and separator meshes.

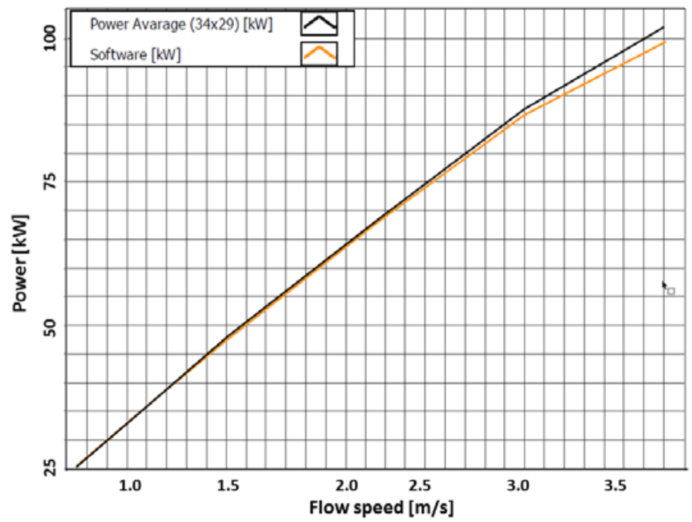

Figure 7: Measured and predicted heat transfer [11]

"High Performance" plate fin/tube coolers

Once the basis standard geometry has been designed and tested, an optimization procedure on the cooler bundle geometry has been carried out. The optimization should not take into account only the single bundle performances (as derived from the experimental tests described above), but the effect of the potential improvement must be assessed and quantified on the overall isotherm compressor performances. This aspect is not trivial because the contribution of the intercooling on the compressor efficiency is not linear and varies with the stage number, individual stage flow coefficient, head rise per stage and overall pressure ratio. In other words, improving the cooling performance of the 1st stage intercooler might not have the same overall effect on stage 3rd etc. For this reason, the cooler optimization has been done together with the compressor performance prediction tool. Each cooler bundle geometry arrangement has been calculated using the prediction tool (Aspen/HTFS) and then implemented in the compressor performance analysis software. A number of geometry parameters were varied as tube diameter, tube pitch/arrangement, tube thickness, fin thickness, fin pitch, number of rows etc. for a total of 29 different configurations. Geometrical constrain of the optimization were the overall dimension of the cooler bundle in length, width and depth. The water velocity was also kept constant (same water flow consumption). For each configuration, the thermodynamic properties of the bundles were calculated and an object function evaluated as follow (eq. 3)s:

$$OF_i = A \cdot h_i - B \cdot \Delta p_i \qquad 3)$$

where "A" and "B" are weighting factors for the cooler heat transfer and pressure drop. Figure 8 shows the variation of the OF for the 29 different configurations.

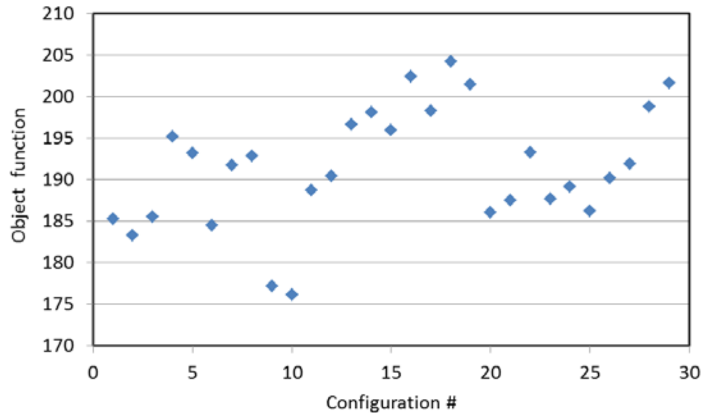

Figure 8: Objective function evaluated for different geometrical configurations

Configurations with the highest OF (#16, 18 and 29) were selected for further analysis on the isotherm compressor performance. The prediction tool for performance evaluation for isotherm compressor showed that the highest benefit is reached with the configuration #16. The overall efficiency increase on the compressor shaft power is between 0.5% and 1%, depending on the cooler loading (i.e. specific volume flow). It is worth to note that in inline isotherm compressors, the overall dimension of the coolers is always the same for a fixed frame size. This means that at different operative points, the thermal load (i.e. the volume flow to be cooled) is different as well as the benefit of the "high performance" geometry.

Cost/benefit analysis for "High performance" coolers

The cost analysis done on the optimized geometry of the "high performance" coolers only shows a cost increases of <20%, compared with the "standard" intercooler geometry. The cost increase comes in fact only from the higher number of tube rows (compared with standard geometry). All manufacturing technologies, procedures and materials, are unchanged compared with standard geometry.

On the compressor side, there is no increase of cost since the casing, stators and rotating components are not affected by this change in intercooler tube/fins layout geometry. Therefore the cost impact of the "high performance" intercoolers on the overall machine is of the order of <1%.

Typical power evaluation used on the bid phase of EPC contractors is, in case of ASU plant, larger than 1500 EUR/kW. This means that 2 or more competitive compressor trains are compared on price and power level by using such parameter to evaluate the difference of power consumption at, normally, design conditions. In practice, that means that an improved in power consumption (efficiency) can be easily evaluated in a significant financial benefit during bid evaluation. For example on a medium ASU plant, the size of the main air compressor is of the order of 25 MW. With a saving in power consumption of 1% (i.e. 250 kW), the financial benefit would be larger than 375 kEUR, which is very attractive being >10% of the total Main Air Compressor price.

Hybrid plate/tubes coolers

As described before, the tube/fins coolers are commonly used for both geared and inline isotherm compressor. A number of alternative technologies are however under investigation and show interesting potential for both performance improvements or cost reduction. One particularly attractive solution is the so called "Hybrid plate/fins" cooler. Hybrid plate/tubes heat exchangers are manufactured by piling and welding several corrugated plates with a given geometry so that cooling media can flow in closed loop path while gas can go through straight "channels" in cross flow. Figure 9 shows a schematic of this arrangement.

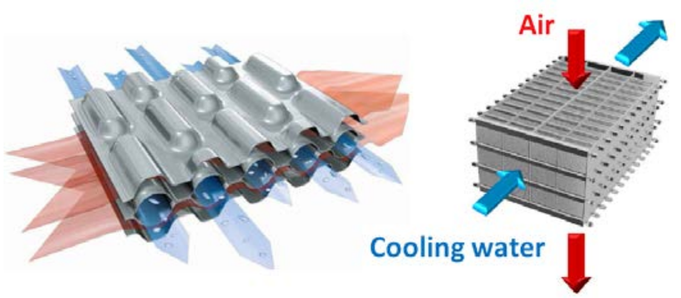

Figure 9: Hybrid plate/tubes concept

With this design, the area ratio between the wetted surfaces of air and coolant is approximately equal to 1, which means that the heat transfer is significantly improved when compared with the classical tube/fins design. The air passages are designed so that they have the lowest pressure losses i.e. the passage is almost "see through". While the water channels, where the pressure losses are much less important, is designed with bumps and curves to increase heat transfer coefficient.

Simulations on the heat transfer coefficient shows that, keeping the same overall dimensions and flow parameters, the heat transfer of the Hybrid plate/tubes is ~200 W/m2K that means a factor 2.5 when compared with the tube/fins arrangement. As a consequence, investigation carried out on axial-radial isotherm compressor [13], with external coolers, shows that an equivalent Hybrid cooler (able to transfer the same overall heat) is approximately half in length compared with the "standard" tube/fins cooler bundle (Table 2 [12]).

Table 2: Comparison between tube/fins and Hybrid coolers for a given geometry and same operating point of an isotherm compressor [13]

	Tube/fins	*Hybrid*
Length [m]	12.5	6.0
Height[m]	4.1	3.7-4.2
Casing diameter[m]	3.1	3.5-4.0
Heat transfer coeff [W/m2K]	81.66	207
Wetted surface [m2]	6600	2663
Material	CuNi/Fin-Al	SS
Air pressure drop [mbar]	54	50.1
Weight [kg]	54000	49000

In inline radial isotherm compressors, the size reduction of the intercoolers is much more beneficial because the casing size can be also decrease, while keeping the rotating component unchanged. A smaller casing design has also a big impact on the overall cost of the compressor, estimated in about 10%.

The disadvantage of the Hybrid plate/tube design is the cost of such arrangement. Estimated cost is about >30% higher than conventional plate fin/tube arrangement.

FOULING

Fouling is commonly known as the accumulation of unwanted material on surfaces as, for example, tubes and pipes. Fouling phenomena are common in different industrial environments, ranging from ship hulls, natural surfaces in the marine environment (marine fouling) and fouling of heat-transfer components through chemicals contained in the cooling water. Fouling in heat exchangers surfaces increases the resistance to heat transfer and therefore a loss in performances (efficiency) which is associated with a significant increase of operating and maintenance costs.

Design of heat exchangers usually take into account the decrease of heat transfer and compensate for it by implementing a larger heat transfer area. This method, although commonly used in all industry areas, is not very convenient since it increases the capital costs of the coolers, overdesign a number of components as water pumps, piping etc as well as the casing of isotherm compressors. In addition, increasing the heat transfer area is no measure to prevent fouling but only to account for it. Therefore a number of preventive measures must be implied as periodic (online or offline) cleaning, water treatments, use of antifouling chemicals in the cooling water etc. All these measures have a high cost and, in some cases, require interruptions in the production which might be very expensive. Therefore a lot of effort is done in several research areas in order to minimize (or even cancel) the detrimental effect of fouling [1].

The difficulty of having a correct estimation of the fouling effect lies in the diversity of fouling behaviour and growth mechanisms linked with several parameters as flow velocity, wall temperature, temperature difference between water and wall, heat flux but also chemical factors as composition, concentration, corrosion and reaction behaviour, growth of micro/macro organisms etc. In literature [16] a classification is done where fouling is categorized in mainly 5 phases (initiation, transport, attachment, removal, ageing) and in 5 different groups (crystallization, particulate, chemical reaction, corrosion and biological).

Another important subject with fouling is the quantification and its modelling, which allows prediction of its behaviour in industrial components, in particular heat exchangers. Normally, when the primary concern is the effect on heat transfer, fouling can be quantified by the increase of the resistance to the flow of heat (m^2K/W) due to fouling (termed "fouling resistance"), or by development of heat transfer coefficient (W/m^2K) with time. Fouling modelisation can be of numerical or experimental nature and is very different if considered, for example, on gas turbine/compressor blades or in non-rotating components as heat exchangers. An extensive analysis of fouling mechanism and modelisation in gas turbine and compressors blades can be found in [10].

TEMA Standards [9] states different fouling factors (in terms of m^2K/W) according to different kind of water used as coolant media, such as river water, seawater, cooling tower water etc as shown in Table 3 [12]. However these values are only an indication and the real fouling resistance found on industrial site is, most of the time, unknown. Typically EPC contractors specify the fouling factor when enquiring rotating machinery.

Table 3: Recommendation for fouling factors in different process fluids according to TEMA standards [12].

Process fluid	*Fouling Factor [m^2K/kW]*
Soft water	0.18–0.35
Cooling tower water	0.18–0.35
Seawater	0.18–0.35
River water	0.35–0.53
Lube oil	0.36
Organic solvents	0.36
Steam (oil bearing)	0.18

Fouling in isotherm compressors

In isotherm compressors, fouling has a detrimental effect because, as explained, decreases the intercooler performances and increases capital and maintenance costs. Normally in tube/fins cooler the fouling on the gas side (fins) is much less important and detrimental compared on the fouling on the water side (inside the tubes). Fouling on the fins is normally neglected and has much lower impact on the heat transfer since the gas wetted surface is much larger than the water wetted surface inside the tubes. For these reasons, the following analysis will consider only fouling factors on the water side.

Specifying too high fouling factor in the design phase of isotherm compressors can lead to negative effects. In fact, since in the first period of compressor operation the tubes are almost clean (no fouling), the water flow should be then reduced by throttling the inlet coolant valve. This leads to a (unexpected) very low water speed, which is actually promoting even more biological and organic fouling.

Accurate quantification of the effect of fouling factor on isotherm compressor in operation is, as explained, a quite challenging task and very rare since precise site data (coolant and flow temperature at the inlet/outlet of the coolers) are seldom available. Two examples are described below where the fouling factor was verified by means of flow measurements and further verification with performance compressor tool.

a) One inline 5-stages air compressor (MAC) has been installed in a petrochemical plant (in Italy) directly on the seaside. The compressor used seawater for the stage intercooling and performance check has been carried out every month using the measured data from site instrumentation. An operation period of 5 years (2007-2012) was considered and afterwards the plant was shut down for maintenance. In 2007 new intercoolers were installed and the data showed a calculated fouling factor of 0.0001 m^2K/W, which was more than 3 times lower than the one specified in the design phase. After 17 month of operation, the calculated fouling factor was 0.00015 m^2K/W (therefore 50% higher than initially evaluated but >2x smaller than specified in the design). In November 2010 (4 years of interrupted operation), the performance evaluation showed a fouling factor of 0.0003 m^2K/W which is close to the initially specified in the design phase. In the following 2 years, the compressor performance did not deteriorate significantly. Inspection of the coolers after this operation period showed a very high fouling inside the tubes due to the seawater cooling media. It was concluded that the initial specified fouling factor was correct for such aggressive (and quite unusual) environment. However most of the isotherm compressors are using cooling tower water or treated water and therefore the specified design fouling factor should be set to a much lower value.

b) Another peculiar example of fouling factor evaluation is given by an isotherm compressor used in nitric acid production plant in Finland. The plant has been operating since year 1999 and has installed an inline 5-stage 3-intercooler air compressor driven by a steam turbine. The original finned/tube intercoolers were replaced with new "standard" plate fin/tube heat exchangers and a high fouling factor was specified in the design phase since the cooling media is seawater from Baltic sea. After the commissioning, the measured air temperature after the cooler was much lower than the calculated one i.e. the cooler performance was much higher than expected. After 1 year of operation, site data were delivered and performance evaluation was done. The results showed that in order to match the measured outlet air temperature, a fouling factor of only 0.00005 m^2K/W had to be specified. The resulting calculated power consumption was 1.5% lower than what evaluated with high fouling factor. This means that the initially specified fouling factor was way too high for this cooling water.

The two examples above show how variable the fouling factor can be and how difficult is its quantification in the design phase. The overall effect of fouling factor on shaft power consumption is summarized in Figure 10. The compressor power is calculated for different casing size and rotors. The same fouling factor is considered for every calculation as reference value (no power difference). By decreasing the specified fouling factor, the compressor power decreases almost linearly with a gradient depending on the intercooler loading. In the ideal case of no fouling factor considered, the power saving reaches a value between 1.4% - 1.8%. Such benefit in power consumption is very high in isotherm compressors and comparable to the efficiency improvement which can be reached by designing a very advanced new radial stage generation. However the R&D cost of complete new radial stage development is also significant and time-to-market of >1year should be considered.

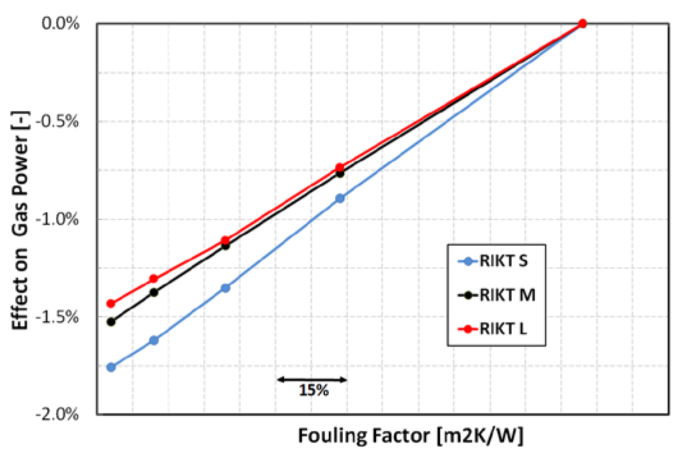

Figure 10: Effect of specified design fouling factor on compressor power consumption

These considerations lead to the conclusion that new developments of minimizing and/or mitigating the effect of fouling in intercoolers are very attractive and reported in several publications [17, 18, 19]. The most common used methods are the following:

- Active tube cleaning and coating
- Cooling water treatment

Active tube cleaning is done with different methods involving mechanical rubbing of the internal tube surface by means of rubber brushes, sponges or balls which are circulating with the cooling water and continuously removes fouling. The system is quite used in power plant applications and seawater condensers, however very rarely in isotherm compressors intercoolers. The cost of the system and its complexity are the main disadvantages. Another strategy of active cleaning is the implementation of spirals inside the tubes which, thanks to the vibration induced by the water flow, are rubbing and cleaning the inner tube surface. These methods however have limited life and are almost never used for isothermal compressor applications.

Another approach to fouling mitigation is the use of coatings on the tube inner diameter. This technology is sometimes used in oil&gas and power plant environment where severe fouling is occurring due to seawater cooling media. Recent developments are focusing on this area and show good potential.

Water treatment is normally used in every plant and the specific process varies depending on the requirements of the water. The treatment removes hardness and silica and/or adjusts the pH as well as filters any suspended particles. At this point in the treatment process, there is typically the use of filters and chemicals, such as:

- Corrosion inhibitors (e.g., bicarbonates) to neutralize acidity and protect metal components
- Algaecides and biocide (e.g., bromine) to reduce the growth of microbes and biofilms
- Scale/fouling inhibitors (e.g., phosphoric acid) to prevent contaminants from forming scale deposits

Using a treatment prior to this stage can help reduce the amount of chemicals needed to treat water at this point in the process, which is normally preferred considering many chemical treatments can be expensive. All these treatments are helping to fight against scale and fouling in the whole plant however the whole system can be very sophisticated and expensive. The system in fact requires also monitoring of chemical residuals, heat exchanger approach temperature, deposit coupons, back pressure feedback etc which are necessary to maintain the water treatment efficient in time. The investment and running costs of such sophisticated systems is very high, therefore simple water treatment is often used on ASU, Steel factories and Ammonia plants which uses isotherm compressors.

CONCLUSIONS

A comprehensive study concerning the effect of different intercooling technologies on isotherm compressors has been carried out. As demonstrated and quantified in the paper, the intercooling process has a great impact on the overall compressor performance as well as capital and operating costs. A 5% increased heat transfer ability of the intercoolers in a 3-stage inline isotherm compressor leads to an overall power saving of >0.6%, which is considered significant.

An optimization process has been carried out for tube/fin coolers by varying a number of geometrical parameters. The cooler data are experimentally verified and the overall compressor performance then evaluated. A benefit in the compressor power consumption up to 1% is reached against a cost increase of less than 20%. This makes this solution very attractive and has been already installed in several inline isotherm air compressors.

Hybrid plate/fins coolers are also analysed in terms of performances and costs. This solution shows great potential of either significantly increase intercooling performance or decrease casing size and therefore capital costs. However the coolers cost level is, at the moment, quite higher than tube/fins coolers.

Great attention is also focused on cooler tube fouling in terms of fouling factor estimation, modelisation and mitigation measures. Site experiences and measured data on isotherm compressors show that this is still a very challenging aspect of coolers design and has a significant effect on the isotherm compressor design and operation.

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NOMENCLATURE

ASU	Air Separation Unit
IGV	Inlet Guide Vane
MAC	Main Air Compressor
BAC	Booster Air Compressor
A,B	Heat transfer and pressure drop weight coefficient
f	Normalized friction factor
IC	Intercoolers
OF	Objective function
Δp	flow pressure drop
ΔT	Temperature difference
ΔPower	Compressor power consumption difference
D_H	Hydraulic diameter
L	Tube length
ρ	Flow density
u	Flow velocity
ϕ	Heat transfer
S	Surface
ΔT	Temperature difference
h	Heat transfer coefficient

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