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THEORETICAL AND EXPERIMENTAL RESEARCH ASPECTS OF COMPRESSOR INSTALLATIONS WITH MULTISECTION GASCOOLERS

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ABSTRACT

Improving the cooling systems is one feasible technique to ameliorate the characteristics of compressor installations. This paper presents the results of theoretical and experimental researches of staged compressed gas cooling process through several coolants with different properties in multisection gascoolers. The theoretical investigation was conducted using a developed mathematical model, which was represented as a system of equivalent mathematical models in three hierarchy levels. The experimental investigation was conducted with two- and trisectional gascoolers based on plate-fin and tube heat exchange surfaces. The complex approach to the multilevel optimization of multisection gascoolers is written.

NOMENCLATURE

\( \rho \) - density, \( w \) - velocity, \( A_f \) - free-flow area, \( D \) - hydraulic (equivalent) diameter of channel, \( \Pi \) - perimeter of channel, \( \xi \) - friction factor, \( \alpha \) - heat transfer coefficient, \( c_p \) - specific heat, \( \dot{Q} \) - heat flux, \( T \) - absolute temperature, \( \lambda \) - thermal conductivity, \( \mu \) - viscosity, \( Re \) - Reynolds number, \( Pr \) - Prandtl number, \( T, t \) - time, \( a_T \) - annual equivalent coefficient, \( c_A, c_P, c_C, c_E \) - unit cost of heat transfer area, pumping power, coolants, electrical energy, \( E \) - energy consumption, \( A \) - multisection gascooler total heat transfer area, \( \dot{V} \) - coolant consumption, \( P \) - power of pump or ventilator.

INTRODUCTION

Staged (combined) compressed gas cooling through several coolants with different properties (for instance, air and water; cold compressed gas, air and water; cooling brine and water; heat transfer fluid and water; etc) in multistage compressor installation has many advantages as compared to conventional unistage water or air cooling [1,2]. The results of research show that in this case may be reducing of the cooling water consumption (by a factor 8-10 and more times) and reducing the scale deposit on the gascooler tube surface as compared to water cooling; reducing of heat exchange surface (by a factor 1.5-5 times) and improving of compressed gas cooling efficiency during the hot months as compared to conventional air cooling. Besides, by staged compressed gas cooling is extending the possibility for recovery and utilizing the compression heat without reducing compressed gas cooling efficiency.

A staged cooling process may be realized in several separated (connected one after another) heat exchangers through which the compressed gas flows or in multisection gascoolers.
second possibility is in most cases preferable. However, the multitude of possible multisection gascooler designs and their arrangement on the compressor requires a thorough investigation of compressor installations with such gascoolers. One of the main tasks in this case is analysis of interaction compressor stages and multisection gascoolers by change of:

- coolant combination, temperatures and consumptions of coolants,
- heat transfer rate in gascooler sections (in consequence of turbulence, constructional and thermodynamic parameters change, contamination in the gascooler pipes through which the coolants flows),
- combination series of gascooler sections,
- interaction of multisection gascoolers in compressor installation.

The selection of multisection gascooler designs may be done on the basis of complex optimization with applying of this analysis results.

**MATHEMATICAL MODEL**

The multisection gascoolers are complexly structured objects with "internal connections". At the same time gascoolers are part of compressor installations and are correlated with compressor stages, therefore they correspondingly have "external connections". A mathematical model (MM) of multisection gascoolers was developed for theoretical investigation of these connections. It was refined as a system of equivalent mathematical models in three hierarchy levels (h=I, II, III) [3]:

- the HES level of heat exchange systems (multisection gascoolers), built up from the heat exchange units, (h=I);
- the HEU level of heat exchange units (gascooler sections), built up from the heat exchange elements, (h=II);
- the HEE level of heat exchange elements (section elements), (h=III).

The mathematical model structure in general form:

1. Mathematical description of multisection gascooler constructional characteristics
   
   \[ MM^C_1 \supset \{ MM^C_{(w)} \supset \{ MM^C_{(ww)} \} \}, \]

   which is founded on the equations as
   
   \[ \dot{F}_{hc} = \dot{f}_{hc}(Z^C_h), \quad h=I, II, III, \]

   where \( F_{hc}, Z^C_{h} \) are constructional characteristics and parameters of HES, HEU, HEE.

2. Mathematical description of compressed gas and coolants interaction scheme in multistage compressor installation
   
   \[ G = \left\{ g_{(1)}, \{ g_{(w)} \} \right\}, \quad g_{(1)} = \left\{ M_{(1)_j} \right\}_j, j = 1, n, \quad g_{(w)} = \{ R_{(w)_i} \}_i, i = 1, m \]

   where matrix \( M_{(1)_j} = (\alpha_{(1)_j}) \) is topological characteristic for \( j \) th multisection gascooler, vector \( R_{(w)_i} = (i_1...i_n) \) is coolant flow sequence through heat exchange elements in \( i \) th section.

3. Mathematical model of heat transfer process in multisection gascoolers
   
   \[ MM^H_1 \supset \{ MM^H_{(w)} \supset \{ MM^H_{(ww)} \} \} \]

   The mathematical model of heat transfer process in HEE (\( MM^H_{(w)} \)) may by represented as one-dimensional differential continuity, momentum and energy equations system for compressed gas and coolant:
\[
\left\{ \begin{array}{l}
\frac{\rho \cdot dw + w \cdot dp + \rho \cdot w \cdot dA_f}{dx} = 0 \\
\frac{\rho \cdot w \cdot dw + dp + \xi \cdot \rho \cdot w^2}{dx} = 0 \\
\frac{\rho \cdot w \cdot (c_p \cdot T) - \alpha \cdot \Delta T \cdot \Pi}{dx} = 0
\end{array} \right. \\
\text{with additional equations:} \\
f_{g,c}(P, \rho, T) = 0; \quad q = -\lambda_w \cdot \text{grad} T; \quad c_{p,c}^g = c_{p,c}^g(T); \\
\lambda_{g,c} = \lambda_{g,c}(T); \quad \mu_{g,c} = \mu_{g,c}(T); \quad \alpha_{g,c} = \alpha_{g,c}(\text{Re,Pr}); \quad \xi_{g,c} = \xi_{g,c}(\text{Re,Pr}); \quad d\dot{Q}_g = d\dot{Q}_c
\]
and with corresponding boundary conditions for HEE.

For mathematical models $MM_{(M)}^H$ and $MM_{(S)}^H$ are used corresponding boundary conditions for HEU and for HES and also additional equations (balance ratio for compressed gas parameters $Z^H$) as:

\[
Z^H_{(M)j-1} = Z^H_{(M)j} - \Delta Z^H_{(M)j}, \quad j = 1, n
\]

\[
Z^H_{(CS)j} = Z^H_{(CS)j+1} - \Delta Z^H_{(CS)j}, \quad j = 1, n
\]

where $Z^H \in \{P, T, m\}$ are thermodynamic parameters of compressed gas (pressure, temperature, mass flow).

4. Mathematical description of thermodynamic connections between multisection gascoolers (MGC) and compressor stages (CS) in compressor installation

\[
R(Z^H_{MGC}, Z^H_{CS}) = 0
\]

which is founded on the balance ratio

\[
Z^H_{(MGC)j} = Z^H_{(CS)j} - \Delta Z^H_{(MGC)j}, \quad j = 1, n
\]

where $\Delta Z^H_{(MGC)j}, \Delta Z^H_{(CS)j}$ are compressed gas thermodynamic parameter variations between compressor stages and multisection gascoolers.

5. Mathematical description of compressor installation economic (thermoeconomic) characteristic

\[
C = C(Z^H_{MGC}, Z^C_{MGC}, Z^H_{CS}, Z^C_{CS}, G_{MGC}, S_{MGC})
\]

where $S_{MGC}$ characterizes a multisection gascooler arrangements in compressor installation.

The developed mathematical model allows to assess the effect of the thermodynamic and structural parameters of the multisection gascoolers, the combination of coolants in them and the arrangement of the compressor installation on its operation under different external conditions.

**EXPERIMENTS**

The experimental investigation was conducted in conformity to tasks, which were described above. First of all, multisection (two- and trisection) gascoolers based on plate-fin and tube heat exchange surfaces were investigated. An influence of coolant combination, coolant and compressed air thermodynamic parameters ( coolant consumption, inlet temperatures) and section combination series in multisection gascoolers were researched under laboratory conditions. For industrial experiment a stationary two-stage piston compressor ($\dot{V}_g = 100\text{m}^3/\text{min}$)
P₂ = 9 bar) was used. The conventional unisectional water-cooled gascoolers were replaced by multisectional (trisectional) gascoolers [4]. The compressed air was cooled in the gascoolers first by cold compressed air, then by atmospheric air and finally cooled to the required temperature by water. Compression heat removed from the first stage of the gascooler was used for increasing the energy of delivered compressed air, and the heat removed from the second stage - for heating the compressor station environment during the cold season. There were two types of multisection gascooler arrangements in compressor station for these experiments:

- multisection gascoolers were arranged on the compressor,
- multisection gascoolers were arranged separately next to wall of compressor station.

Experiments were conducted by different external conditions of compressor installation’s operation over quite a long period of time.

OPTIMIZATION

Optimization was performed on the basis of a developed complex approach, offering selection of optimal multisection gascooler designs, the optimal combination of coolants and their features and the optimal arrangement of gascoolers [5,6].

The aim of optimization is to find the extremum of the objective function

\[ \Psi = \text{opt}\Psi \left( Z_{MGC}^H, Z_{MGC}^C, G_{MGC}, S_{MGC}, Z_{CS}^H, Z_{CS}^C, B \right) \]

by following restrictions are imposed on the optimization parameters:

\[ N_1 (Z_{MGC}^H, Z_{MGC}^C, G_{MGC}, S_{MGC}) = 0, \quad l = 1, r \]

\[ N_1 (Z_{MGC}^H, Z_{MGC}^C, G_{MGC}, S_{MGC}) \geq 0, \quad l = r + 1, L \]

for concrete compressor with thermodynamic and struktural parameters \( Z_{CS}^H = Z_{CS}^{H(0)} \), \( Z_{CS}^C = Z_{CS}^{C(0)} \) and for concrete external conditions (climatic data, compressor installation conditions of operation, compression heat utilizing conditions) \( B = B_0 \).

Due to the chosen hierarchy of the multisection gascoolers may be six main optimization task types \( R_u \Rightarrow \{ R_{uh} \}, \quad u = 1, 2...6; \quad h = J_{up}...J_{low} \)

<table>
<thead>
<tr>
<th>Hierarchy level of MGC</th>
<th>Optimization tasks of MGC</th>
</tr>
</thead>
<tbody>
<tr>
<td>HES (h=I)</td>
<td>R_1, R_2, R_3, R_4, R_5, R_6</td>
</tr>
<tr>
<td>HEU (h=II)</td>
<td>R_1(II), R_2(II), R_3(II)</td>
</tr>
<tr>
<td>HEE (h=III)</td>
<td>R_1(III), R_2(III), R_3(III)</td>
</tr>
</tbody>
</table>

These tasks differ from combination of hierarchy levels, therefore they have different combination of optimization parameters (independent variables) \( Z_u \Rightarrow \{ Z_{uh} \} \) and optimization criterions \( \Psi_u \Rightarrow \{ \Psi_{uh} \} \). The major optimization criterion for tasks \( R_1...R_6 \) is economic criterion \( \Psi_{\text{C-comp}} = C_{\text{comp}} \). It characterizes the annual total cost of compressor installation operation.

It is defined from equation:

\[ \Psi_{\text{C-comp}} = \alpha_f \left( \sum_{j=1}^{n} A_j \cdot c_{df} + \sum_{j=1}^{m} \sum_{i=1}^{P} P_{ij} \cdot c_{pf} \right) + \left[ \sum_{j=1}^{n} \sum_{i=1}^{m} \hat{E}_{ij}^C(t) \cdot c_{gi} + \sum_{j=1}^{n} \sum_{i=1}^{m} \hat{E}_{ij}^P(t) \cdot c_{pi} + \sum_{j=1}^{m} \hat{E}_{ij}^C(t) \cdot c_{gi} \right] \cdot dt \]
Beseides, for every level additional criterions are used:

- for HES level: exergy effiency of compressor installation, annual power expended on compressor installation, annual water consumption, multisectional gascooler total heat transfer area;
- for HEU level: heat exchange unit effectiveness, ratio of gascooler sections total heat transfer area to the volume of the gascooler section;
- for HEE level: energy effectiveness.

Optimization tasks dimension is reduced by applying the found heuristics

**DISCUSSION**

The theoretical and experimental investigations of multisection gascoolers allowed to obtain the following results.

1. The change of heat exchange effectiveness in $i$th section of MGC is smoothing in $(i+1)$th and following sections. The influence of this change on compressed gas outlet temperature in $j$th MGC may be find from equation:

$$\Delta T_{MGC_j}^{(out)} = \Delta T_{ji}^{(out)} \cdot \prod_{x=i+1}^{m}(1 - \varepsilon_x), i = 1, m; \quad j = 1, n.$$  

Therefore, the last section $(i = m)$ in $j$th MGC plays a essential part and it compensates the change for the worse of compressed gas cooling (for instance, in consequence of compression heat utilizing) in previous $(i = 1, m - 1)$th sections. Thus, the most heat exchange effectiveness of $j$th MGC may be achieved by condition:

$$\left( (T_{g}^{(in)} - T_{g}^{(in)})_{ji} = \min(T_{g}^{(in)} - T_{g}^{(in)})_{j}, f = 1, m. $$

Besides, the following inference could be done: in some times the biggest heat exchange effectiveness of MGC may be achieved by change of compressed gas flow sequence through sections in MGC. For instance, for two-section MGC with two coolants (air and water) this change is realized by condition: $T_{air}^{(in)} = T_{water}^{(in)}$.

2. In case of compressed gas cooling in MGC through several coolants, including air ($f = (m_e - 1)$) and water ($f = m_e$), it is worth while by condition $T_{air} \leq T_{air}^0$ to shut off a water (for instance, for researched trisection gascoolers $T_{air}^0 \approx (260..270)K$).

3. The interaction different MGC through coolants in compressor installation is preferable by parallel-flow of compressed gas and coolant in compressor installation.

4. In case, when $\dot{V}_e(t) = \text{const}; f = 1, m_e; \quad t \in (0, T)$ outlet temperatures difference

$$\Delta T_{MGC}^{(out)}(s_{var}, s_{const}) = 100\% \cdot \left\{ \left[ T_{MGC}^{(out)}(t) \right]_{s(t) = \text{var}} - \left[ T_{MGC}^{(out)}(t) \right]_{s(t) = \text{const}} \right\} / \left[ T_{MGC}^{(out)}(t) \right]_{s(t) = \text{const}} \approx 1\%.$$  

Thus, for calculation of MGC thermodynamic parameters by $T_{air} = T_{air}^0$ (where $T_{air}^0$ is air temperature for calculation of MGC structural parameters) may be used $s(t) = s(t_0) = \text{const}$. It allow to simplify numerical investigation and optimization of MGC.

**CONCLUSIONS**

The evolution of compressor installations which do not require large amounts of cooling water and ensure utilizing the heat generated by compression without reducing compressed gas
cooling efficiency may be achieved by employing a staged (combined) compressed gas cooling process through several coolants with different properties in multisection gascoolers. The results obtained from theoretical and experimental investigations as well as the described complex approach to the optimization of such gascoolers allow to find the most effective employment of multisection gascoolers in compressor installations.

REFERENCES

5. V. Parfenov. The methodological basis of a complex approach to the problem of combined coolers for compressor installation design. Compressor equipment and pneumatics, N 3, 1994, pp.9-17.