Weight and size characteristics modelling of the power plants contact condensers

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Abstract. The article presents the fundamental principles of mixing condensers calculation. The design calculation flow chart of apparatuses of this type is proposed. A good convergence of the droplet motion hydromechanics with the other authors works results is identified. The operating conditions calculation results of the contact condenser as a part of the chemical energy unit with hydrocarbon raw material partial oxidation showed that mass transfer impact on the heat exchange is quite significant (the Gukhman criterion is 0.0076), which affects the high process intensity (heat transfer coefficient is ~179 W/(m²°C)). However, as expected, the device is characterized by the low resistance of ~6 Pa.

Key-words: gasification, heat-exchange, waste heat boiler, condenser, algorithm

1. Introduction
Modern heat and power complexes include gas-turbine plants with steam supply to the combustion chamber (STIG scheme) [1, 2]. In this case, steam injection into the combustion chamber substantially increases the turbine specific capacity due to the working body increase; blades and flame tube walls air cooling changing into the steam cooling makes it possible to grow the working body temperature; steam inlet into the oxidation zone helps to reduce the nitrogen oxides emission [3]. The exhausted combustion products deep heat recovery system based on the traditional waste heat boiler and contact condenser is a key element of the mentioned complexes. A similar system is proposed for application in the complex chemical energy use schemes of the hydrocarbon raw materials with air-steam gasification [4], since under the certain operating modes, water vapour content in the reaction products is from 33 to 47 vol. % and it must be returned to the main energy cycle. However, if the waste heat boilers design calculation is a traditional task and has already been carried out taking into account the synthesis gas thermal and physical characteristics [5], a small number of works is devoted to modelling the contact heat exchangers and particularly packless ones.

2. Problem statement
Taking into consideration the foregoing, performing the contact condenser volume processes modelling and defining the condenser weight and size characteristics determining the apparatus cost seems to be relevant. The apparatus scheme and working bodies flows are represented in figure 1. The apparatus packless design was chosen on the basis of the gas path aerodynamic resistance minimizing considerations, although in this case the heat exchange intensity decreases as compared to the packless apparatuses.

The scrubbing liquid (water) can serve as an absorbent for extracting the undesirable components from the total or partial oxidation products, and the contact condenser is in fact the upstream first purification stage before the absorber, where the dead weight impurities content of the synthesis gas is...
reduced to the required values. Taking into account the synthesis gas content and individual solubility coefficients [6], one can expect the predominant absorption of carbon dioxide. In the hollow condenser, when absorption phenomena occur in the spray opposite direction of the gas phase motion, counter flow is theoretically carried out. Nevertheless, as a result of gases circulation and mixing, such devices are similar to the complete mixing devices by the phases interaction type and they have lower mass exchange effective driving force than the packless devices have under the proper counterflow [7].

![Figure 1](image)

**Figure 1.** Mixing packless condenser: 1 is the synthesis gas inlet from the waste heat boiler; 2 is the synthesis gas outlet; 3 is the cooling water inlet; 4 is the heated water and condensate outlet.

The contact condenser organization according to this scheme will make it possible:
- to conduct flexible temperature control and CO₂ content by changing the spray water flow;
- to exclude or minimize the moisture separators volumes, since the main part of the water vapour condensate is removed with irrigation water into the storage tank;
- to have the mixing apparatuses smaller metal consumption in comparison with the recuperative heat exchangers one, this causes the capital costs reduction and provides ease of operation and scheme high reliability.

Thus, the calculation task is to define the diameter and height of the apparatus cylindrical section, as well as CO₂ content of the exhaust synthesis gas. Besides, it is necessary to consider that the steel grade and the thickness of the construction elements determining the apparatus cost should be chosen on the assumption of the corrosion activity and synthesis gas pressure.

### 3. Theory

For achieving the objective, the contact condenser calculation flow chart was developed (figure 2). The calculation is based on the heat balance equation and gas and liquid temperatures logarithmic mean difference as the simplest and most reliable method of defining the process driving force [8]. Gas phase thermal and physical properties are calculated according to the recommendations set forth provided in paper [9].
Figure 2. The flow chart of mixing heat exchanger-condenser calculation.

For calculating the droplet motion hydromechanics, one can use the graphical dependence of $\ln Re_{fl} = f(\ln Fe)$ [10], where the Reynolds criterion corresponds to the liquid droplet floating velocity $w_{fl}$ and the Fedorov criterion determining the beginning of the droplet gravitational equilibrium and gas medium resistance can be represented in the following form:

$$Fe = d \cdot \left( \frac{4 \cdot g \cdot (\rho_d - \rho_g)}{3 \cdot \rho_g \cdot \nu^2} \right)$$

where $d$ is the liquid droplet diameter, m; $g$ is the gravitational acceleration of the gravity field, 9.81 m/s$^2$; $\rho_d$, $\rho_g$ are the densities of the sprayed liquid droplets and gas phase, kg/m$^3$; $\nu$ is the gas kinematic viscosity coefficient at the gas average temperature in the apparatus, m$^2$/s.

For atomization the liquid in scrubbers, the mechanical atomizers through which the liquid is sprayed owing to its increased pressure (for water in scrubbers from 3 to 5 at.) are most widely used. The apparatus droplets size due to breaking varies in a wide range from 1 to 150 $\mu$m. Determining the drops average diameter is difficult, since their formation depends on many factors. The droplets diameter $d$ when sprayed by the mechanical atomizers is possible to be determined in the first approximation by the formula [8], m:

$$d = 8 \cdot g \cdot k \cdot \frac{\sigma}{\rho_g \cdot \nu^2}$$

where $\sigma$ is the surface tension, kg/m; $\nu$ is the outflow velocity, m/s; $k$ is the coefficient depending on the liquid surface tension, for example, for water $\sigma = 0.00745$ kg/m, and $k = 2.5$.

Since defining the droplet calculated diameter depending on the atomizer type and liquid pressure before the atomizer is particularly difficult, for approximate calculations the droplet average diameter can be determined according to the following formula [10], m:

$$d = \frac{3 \cdot 10^2}{p}$$

where $p$ is the liquid pressure before the atomizer, Pa.
An alternative method of calculating the floating Reynolds criterion is based on the empirical relations [7] depending on the motion nature:

- **Laminar (Stokes’ law)**: \( \text{Re}_{fl.} < 2 \), \( \text{Ar} < 36 \), \( \text{Re}_{fl.} = 0.056\text{Ar} \)
- **Intermediate (Allen’s law)**: \( 2 \leq \text{Re}_{fl.} < 500 \), \( 36 \leq \text{Ar} < 83000 \), \( \text{Re}_{fl.} = 0.152\text{Ar}^{0.715} \)
- **Turbulent (Newton’s law)**: \( \text{Re}_{fl.} > 500 \), \( \text{Ar} > 83000 \), \( \text{Re}_{fl.} = 1.74\text{Ar}^{0.5} \)

Furthermore, Archimedes criterion is defined according to the ratio: \( \text{Ar} = \frac{g \cdot d^3 \cdot (\rho_d - \rho_g)}{v^2 \cdot \rho_g} \).

When the conducted calculations are in the droplets diameter range from 0.6 to 5.5 mm, the difference between the floating Reynolds criteria calculated by both methods was \( \pm 6\% \), correspondingly.

For the chosen counterflow scheme of the phases contact organization, the droplet actual falling velocity and droplet falling velocity with regard to gas are calculated by the equations, m/s:

\[
\text{w}_{ac} = \text{w}_{fl} - \text{w} \quad \text{and} \quad \text{w}_{a} = \text{w}_{fl} + \text{w} \quad (4)
\]

where \( \text{w} \) is the gas phase velocity, it is accepted according to [8] at the level of 1 m/s.

The presented above ratios characterize the solid particles motion. Liquid drops, unlike the solids can deform and grow or fragment during motion, which results in the resistance coefficient and floating velocity change. It was shown in [7] that the surface tension and sprayed liquid viscosity at \( \text{Re}_{fl.} > 500 \) impact the resistance coefficient value. Paper [11] shows that the liquid droplets fragmenting probability is high when the Weber numbers exceed 10. In the conducted calculations the Weber number varies from 0.002 to 8.689 at the droplets diameter from 0.6 to 5.5 mm, correspondingly and therefore droplets do not fragment. It should be noted that in the experiments described in [11] the droplets initial characteristic dimensions of the examined liquids range from 3 to 6 mm and the droplets motion initial velocity is from 0 to 3 m/s, which corresponds to the obtained droplets diameters from 0.6 to 5.5 mm at the droplets motion initial velocity from 8 to 24 m/s.

The active volume of the packless condenser is defined by the following equation, m³:

\[
V = \frac{Q}{\alpha \cdot F_d \cdot \Delta T \cdot \varphi} \quad (5)
\]

where \( Q \) is the amount of heat transferred in the scrubber, kW; \( \alpha \) is the heat-transfer coefficient, W/(m²°C); \( F_d = \frac{6}{d} \cdot \frac{1}{w_{ac}} \cdot H_w \) is the liquid droplets surface in 1 m³ of the condenser volume, m²/m³; \( H_w \) is the liquid spray rate, l/(m²·s); \( \Delta T \) is the heat carriers average temperature difference, °C; \( \varphi \) is the coefficient taking into account the apparatus heat-mass exchange processes imperfection is accepted at the level from 0.85 to 0.95.

The apparatuses having the similar design and operating at the gas velocities up to 5.5 m/s with high liquid spray rates reaching the values from 30 to 45 m³/(m²·h) were tested and implemented [7] as compared to the previously used ones of 10-20 m³/(m²·h).

When calculating the heat transfer coefficient from gas to the liquid droplet under the forced convection conditions for substituting into equation (3), A.V. Nesterenko’s formula can be used [10]:

\[
\text{Nu} = 2 + A \cdot \text{Re}_o^{0.33} \cdot \text{Pr}^{0.33} \cdot \text{Gu}^{0.175} \quad (6)
\]

where \( \text{Nu} = \text{ad}/\lambda \) is the Nusselt criterion; \( \lambda \) is the gaseous heat conduction coefficient at the average temperature between the droplets surface and gas phase, W/(m·°C); \( \text{Re} = \text{w}_d / v \) is the Reynolds criterion; \( \text{Pr} = v / a \) is the Prandtl number; \( a \) is the gas phase thermal diffusivity coefficient, m²/s; \( \text{Gu} = 1 - \frac{T_w}{T_d} \) is the Gukhman criterion taking into consideration the mass exchange impact on the heat exchange; \( T_w, T_d \) are the gas average temperatures on the dry-bulb and wet-bulb thermometers, K.
The numeric values $A$ and $n$ depend on the value $Re$ and are provided below:

| Interval $Re$ | $A$ | $n$ |
|--------------|-----|-----|
| $1 - 200$    | 1.05| 0.50|
| $200 - 25000$| 0.385| 0.57|
| $25000 - 70000$| 0.102| 0.73|

The condenser active height is determined on the basis of the industrial application experience of this type of apparatuses taking into account that the height (H)-diameter (D) ratio should not be less than 1.5-2 and more than 5-7 for the uniform distribution of gas and liquid along the apparatus section [8].

An important stage of the hollow spray condenser calculation is defining the hydraulic resistance. According to the results of Yu.G. Fialkov’s research, the condenser cylindrical section resistance is determined by the following formula:

$$\Delta p = \zeta \cdot \frac{H \rho_v \cdot w^2}{D}$$  \hspace{1cm} (7)

where $\zeta$ is the resistance coefficient assumed at the level of 1.65 [7].

The strength calculation is performed according to [12] and the elliptic flanged bottoms main dimensions and mass should be chosen in accordance with [13].

4. Experimental results

The calculation results by applying the developed algorithm and the ratios (1)-(7) at the partial oxidation reactor gas condensate flow rate of 1400 kg/h; oxidizer consumption coefficient of 0.5; water vapour supply of 3 kg/kg of gas condensate; compressor pressure increase rate of 15; gas turbine pressure decrease rate of 3; droplet average diameter of 5.5 mm; liquid phase average density of 1013 kg/m$^3$; inlet gas and liquid temperature of 120 and 15 °C and outlet one of 20 °C correspondingly; synthesis gas average consumption of 3.825 kg/s; the inlet synthesis gas composition of H$_2$=14.6, CO=6.4, N$_2$=39.3, H$_2$O=33 and CO$_2$=6.7 mol.%; calculated pressure of 0.6 MPa; apparatus steel grade of 09G2S; corrosion allowance of 3 mm are represented in Table 1. The mixing heat exchangers important characteristic determining the overall efficiency is the liquid spray rate assumed in the calculations at the level of 45 m$^3$/m$^2$.h.

| Parameter                          | Symbol | UM | Value |
|-----------------------------------|--------|----|-------|
| Diameter                          | D      | m  | 4     |
| Active part height                | H      | m  | 6.636 |
| Shell wall thickness              | $s_o$  | mm | 12    |
| Bottom well thickness             | $s_b$  | mm | 16    |
| Apparatus mass                    | m      | kg | 12533 |
| Active part volume                | V      | m$^3$ | 83.348  |
| Gas velocity                      | $w$    | m/s| 1     |
| Apparatus hydraulic resistance    | $\Delta p$ | Pa | 5.719  |
| Weber number                      | We     |    | 8.689 |
| Reynolds criterion                | Re     | -  | 4891.526 |
| Prandtl criterion                 | Pr     | -  | 1.136 |
| Gukhman criterion                 | Gu     | -  | 0.0076 |
| Nusselt criterion                 | Nu     | -  | 23.659 |
| Heat transfer coefficient         | $\alpha$ | W/(m$^2$.°C) | 178.779 |
| Heat capacity                     | Q      | kW | 3227.71 |

Estimated calculations revealed that CO$_2$ is removed in the contact condenser by means of dissolving it in water. For example, if CO$_2$ flow rate at the condenser inlet is 0.600 kg/s [4], its outlet flow rate is 0.506 kg/s.
5. Results discussion
Thus, based on the conducted preliminary studies results, it can be concluded that the contact condenser in the hydrocarbon raw material power-engineering use scheme possesses the high heat exchange capacity of \(~179\text{W/(m}^2\text{\cdot°C)}\) and low hydraulic resistance of \(~6\text{ Pa}\). It should be noted that the contact condenser reduces the acid components content (CO\(_2\)) by 15.7 rel. %. This circumstance makes it possible to reduce the load upon the absorbers and thereby improve the unit feasibility parameters.

6. Conclusions
It can be concluded that the developed calculation method allows conducting the calculations of the contact packless heat-exchangers integrated into the schemes CCGT-STIG or chemical energy units with hydrocarbon raw material partial oxidation.

7. References
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