Experimental study of the aerodynamic resistance of a conical-spiral heat exchanger of the outgoing flue gases

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Abstract. An experimental study to determine the pressure loss of the flue gas heat exchanger proposed design in a collective chimney has been performed. The aerodynamic drag factor of a cone-spiral heat exchanger for the household boilers exhaust flue gases heat has been determined on the obtained experimental data basis.

Introduction
Housing and communal services is one of the largest consumers of energy resources in the country, and the issues of energy conservation in this area are relevant. With modern high-rise residential construction for heating apartments, a decentralized heat supply scheme is becoming increasingly popular due to individual boilers installed in each apartment. Such a scheme is very effective both from the point of view of the coolant transportation, and in terms of the gas combustion efficiency. However, the heat utilization issue from the domestic boilers’ flue gases having a significant temperature has not been well understood yet.

Analysis of publications
The decentralized heat supply scheme implementation at the expense of individual boilers installed in each apartment, according to [1], is possible only with the use of a collective chimney, which collects flue gases from the boilers located along a single riser at the residential house entrance. Collective chimney collects the entire flue gases volume, which has a significant temperature (90-120 C) and throws them into the atmosphere. In modern sources there are many publications on the economizers’ selection and calculation, water heaters, etc. for industrial boilers operating on different types of fuels, however, no technical means for utilizing the household boilers exhaust flue gases heat are described.

Purpose and statement of the problem
The aim of the work is to determine the flue gases heat exchanger proposed design aerodynamic resistance. The task is to determine the aerodynamic drag factor of a cone-spiral heat exchanger for the household boilers flue gas heat based on the obtained experimental data.

Method of research
The research method is a statistical analysis of the experimental data obtained from the flue-gas heat utilized.
Main part
Figure 1 shows the household boilers flue gases heat utilization proposed scheme.

![Scheme of flue gas heat exchanger](image)

**Figure 1.** Scheme of flue gas heat exchanger: 1 - external truncated cone, 2 - internal truncated cone, 3 - conical-spiral pipe - heat exchanger, 4 – air duct reducer unit, 5 - cover - ejector, 6, 7 - nozzles of inlet and outlet of the heated heat carrier.

The proposed device for the household boilers flue gases recovery [2] consists of a body formed by two truncated cones of different diameters with identical taper angles arranged coaxially, the bases of which lie in the same plane, a copper pipe is wound between the cones so that it falls to the truncated along the outer cone inner surface, and rises along the inner cone outer surface in a staggered manner and goes outside the heat exchanger, on the cones bases, a cover is placed - an ejector, on the side of the outer side of which an ejection slot is made, at the bottom a cone-shaped air duct reducer unit is attached to the truncated part of the outer cone.

The heated flue gases, rising along the smoke channel, are divided by a cone-shaped air duct reducer unit 4 into two streams, one of which enters the annular space formed by the outer truncated cone 1 and the inner truncated cone 2 located coaxially, the second bypasses the heat exchanger outside. In the annular space, the stream that entered the heat exchanger washes the spatially-spiral-wound copper pipe - heat exchanger 3, giving off heat and heating the heat carrier. Then, the already cooled stream enters the upper chamber of the heat exchanger, from where it is ejected through a slit in the lid - ejector 5 into the flow of flue gases, bypassing the heat exchanger outside. The ejection effect is achieved by accelerating the flue gases flow, bypassing the heat exchanger outside, due to the passage narrowing in the heat exchanger upper chamber maximum expansion place. The hole formed by the truncation of the inner cone 2 serves to stabilize the flue gases flow and reduce the pressure loss. The device component parts characteristic dimensions are determined depending on the amount of flue gases and the diameter of the smoke channel.

The heat exchanger installation in the flue channel will inevitably lead to the available pressure loss, which in turn can cause the flue channel thrust tilting [11].

The aerodynamic drag $\zeta$ (Zeta) factor is determined experimentally for specific cases and determines the pressure loss in the dynamic pressure local resistance in fractions [1]. Knowing the
pressure loss in the local resistance, in our case - the heat exchanger, according to Equation 1, it is possible to determine the aerodynamic drag \( \zeta \) factor.

\[
\Delta P_{he} = \zeta \cdot \frac{\rho v^2}{2},
\]

Where

\[
\zeta = \frac{2 \Delta P_{he}}{\rho \frac{v^2}{2}}
\]

where \( \Delta P_{he} \) – is pressure loss on the heat exchanger, Pa; \( \zeta \) – defines the heat exchanger factor of aerodynamic resistance; \( \rho \) – is flue gases density at the given temperature and pressure, kg/m\(^3\); \( v \) – is the flue gases velocity before the heat exchanger, m/s.

We express the velocity of the flue gas \( v \) through the mass flow flue gas \( m_{fg} \):

\[
m_{fg} = v \cdot S_{fd} \cdot \rho = v \cdot \frac{\pi \cdot d_{fd}^2}{4},
\]

Where

\[
v = \frac{4 \cdot m_{fg}}{\pi \cdot \rho \cdot d_{fd}^2},
\]

Where \( m_{fg} \) – is the mass flue gases flow, kg/s; \( \rho \) – is density of flue gases at the given temperature and pressure, kg/m\(^3\); \( S_{fd} \) – is the flue duct area, m\(^2\); \( d_{fd} \) - is the flue duct diameter, m; \( \pi \) – is number Pi.

Substituting Equation 4 into Equation 2 we obtain:

\[
\zeta = \frac{2 \Delta P_{he} \cdot \frac{1}{4 \cdot m_{fg}} \cdot \frac{1}{\pi \cdot \rho \cdot d_{fd}^2}}{2 \Delta P_{he} \cdot \frac{1}{\pi \cdot \rho \cdot d_{fd}^2}} = \frac{2 \Delta P_{he} \cdot \frac{(\pi \cdot \rho \cdot d_{fd}^2)^2}{4 \cdot m_{fg}}}{2 \Delta P_{he}} = \frac{\pi^2 \cdot \rho^2 \cdot d_{fd}^4}{16 \cdot m_{fg}^2},
\]

Where

\[
\zeta = \frac{\pi^2 \cdot \rho^2 \cdot d_{fd}^4}{16 \cdot m_{fg}^2}
\]

Using the experiment planning theory [12] it is possible to define the pressure loss \( \Delta P_{he} \) behavior mathematical model on the heat exchanger depending on the flue gases amount \( m_{fg} \) and compensation openings in the heat exchanger inner cone \( S_{co} \).

The factors variation levels are presented in Table 1.

| The factors levels          | Factors |
|-----------------------------|---------|
|                             | \( X_1, [\text{kg/s}] \) | \( X_2, [\text{cm}^2] \) |
| Basic (zero)                | 0.0715  | 4.85   |
| Lower                       | 0.033   | 0.27   |
| Top                         | 0.11    | 15.11  |
| The variation range         | 0.077   | 14.85  |

Where \( X_1 \), kg/s - mass flow of flue gases through the site with a heat exchanger \( (m_{fg}) \); \( X_2 \), cm\(^2\) - the area of the compensation hole in the heat exchanger inner cone \( (S_{co}) \).

The second-order orthogonal plan with three experiments in the center of the plan was used for the experiment. According to [12], for the number of factors \( k=2 \) and \( n_0 = 3 \), the magnitude of the star arm is \( \alpha = 1,148 \approx 1,15 \), so the planning matrix looks (Table 2) as follows:
Table 2. The orthogonal plan of the 2\textsuperscript{nd} order for the two factors and with three experiments in the plan center

| Experiment # | Factors (coded values) | Factors (natural values) | Response $\Delta P_{ws}$, Pa |
|-------------|------------------------|--------------------------|-----------------------------|
|             | $X_1$ | $X_2$ | $X_1$, [kg/s] | $X_2$, [cm$^2$] |                                  |
| The core of the plan | 1 | -1 | -1 | 0.033 | 0.27 | 2.51 |
| | 2 | 1 | -1 | 0.11 | 0.27 | 26.36 |
| | 3 | -1 | 1 | 0.033 | 15.11 | 2.39 |
| | 4 | 1 | 1 | 0.11 | 15.11 | 25.22 |
| Siderial points | 5 | $\alpha = +1.15$ | 0 | 0.1216 | 4.85 | 31.93 |
| | 6 | $\alpha = -1.15$ | 0 | 0.0215 | 4.85 | 1.07 |
| | 7 | 0 | $\alpha = +1.15$ | 0.0715 | 19.3 | 8.87 |
| | 8 | 0 | $\alpha = -1.15$ | 0.0715 | 0.0001 | 11.33 |
| The plan centre | 9 | 0 | 0 | 0.0715 | 4.85 | 11.17 |
| | 10 | 0 | 0 | 0.0715 | 4.85 | 10.88 |
| | 11 | 0 | 0 | 0.0715 | 4.85 | 11.48 |

To process the experiment results, the methodology described in [1] was used. Then, substituting the accepted and deduced data, the actual results of the experiment $Y_j$, obtained in the experiments course, the following matrix of the plan of the experiment was obtained (Table 3):

Table 3. Matrix of the 2\textsuperscript{nd} order orthogonal plan in coded values

| Experiment # | Factors | Result $Y_j$, [oC] | Result $Y_j^*$, [oC] |
|-------------|---------|---------------------|----------------------|
| The plan core | $X_0$ | $X_1$ | $X_2$ | $X_{12}$ | $X_1'$, | $X_2'$ | $Y_j$, | $Y_j^*$, |
| | | | | | | | | |
| 1 | 1 | 1 | -1 | -1 | 1 | 0.4 | 0.4 | 2.51 | 2.64 |
| 2 | 1 | 1 | 1 & 1 | -1 | -1 | 0.4 | 0.4 | 26.36 | 27.88 |
| 3 | 1 | -1 | -1 | 1 | -1 | 0.4 | 0.4 | 2.39 | 1.92 |
| 4 | 1 | 1 | -1 | 1 | 1 | 0.4 | 0.4 | 25.22 | 26.14 |
| Siderial points | 5 | 1 | $\alpha = +1.15$ | 0 | 0 | 0.7225 | -0.6 | 31.93 | 30.18 |
| | 6 | 1 | $\alpha = -1.15$ | 0 | 0 | 0.7225 | -0.6 | 1.07 | 1.74 |
| | 7 | 1 | 0 | $\alpha = +1.15$ | 0 | -0.6 | 0.7225 | 8.87 | 9.87 |
| | 8 | 1 | 0 | $\alpha = -1.15$ | 0 | -0.6 | 0.7225 | 11.33 | 11.28 |
| The plan centre | 9 | 1 | 0 | 0 | 0 | -0.6 | -0.6 | 11.17 | 10.57 |
| | 10 | 1 | 0 | 0 | 0 | -0.6 | -0.6 | 10.88 | 10.57 |
| | 11 | 1 | 0 | 0 | 0 | -0.6 | -0.6 | 11.48 | 10.57 |
Yj′, oC – are the values of the estimated response found by the model after processing of experimental data.

Importance of coefficients in the regression equation \( Y' = b_0 + b_1X_1 + b_2X_2 + b_{12}X_{12} + b_{11}X_{11} + b_{22}X_{22} \) was tested by Student criterion:

\[
t_l = \frac{|b_l|}{S_{bl}}.
\]

(6)

The reproducibility variance \( S^2_{repr} \) by three parallel experiments at the central plan point was found for this purpose:

\[
S^2_{bocn} = \frac{\sum_{d=1}^{3}(Y_{0i} - \bar{Y}_0)^2}{3 - 1} = \frac{1}{2} \left[ \sum_{i=1}^{3} y_{0i}^2 - \frac{1}{3} \left( \sum_{i=1}^{n} Y_{0i} \right)^2 \right] = \frac{1}{2} \left[ ((11,17)^2 + (10,88)^2 + (11,48)^2) - \frac{1}{3} (11,17 + 10,88 + 11,48)^2 \right] = 0,0900333
\]

(7)

and calculated the variances and mean square deviations for each of the coefficients.

Because the critical value is \( t_{0,05;3-1} = 4,303 \) (0,05:2) = 4,30265273, 0,05 – was probability, 2 – was a freedom degrees number, then all coefficients in the regression equation can be considered significant except \( b_{12} \).

Therefore, the final regression equation will have the form:

\[
Y' = 13,019 + 12,366 \cdot X_1 - 0,615 \cdot X_2 + 4,075 \cdot X_{11} - 0,784 \cdot X_{22}.
\]

(8)

The adequacy of the equation was checked by Fisher's criterion \( F = S^2_{ad}/S^2_{repr} = 1,53/0,0900333 = 16,998. \) The equation is adequate because the obtained F-ratio is less than the theoretical one \( F < F_{0.05;m_1=6,m_2=2} = 19,329, \) were 0,05 – probability; \( m_1 = 11 - 5 = 6 \) – number of degrees of freedom of adequacy variance; \( m_2 = 3 - 1 = 2 \) – the number of freedom degrees in the reproducibility variance.

Substitute natural expressions in expression (8) instead of \( Y', X_1 \) and \( X_2 \) and taking into account the previously entered relations for \( X_{11} \approx X_1^2 - 0,6 \) and \( X_{22} \approx X_2^2 - 0,6, \) the following equation is obtained:

\[
\Delta P_{he} = 15,934 + 12,366 \cdot m_{fg} - 0,615 \cdot S_{co} + 4,075 \cdot m_{fg}^2 - 0,784 \cdot S_{co}^2.
\]

(9)

Converting the obtained expression of pressure loss on the heat exchanger and the Eq. 5 is obtained:

\[
\zeta = (15,934 + 12,366 \cdot m_{fg} - 0,615 \cdot S_{co} + 4,075 \cdot m_{fg}^2 - 0,784 \cdot S_{co}^2) \cdot \frac{\pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2}
\]

\[
\frac{15,934 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} + \frac{12,366 \cdot m_{fg} \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} + \frac{4,075 \cdot m_{fg}^2 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} - \frac{0,615 \cdot S_{co} \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} - \frac{0,784 \cdot S_{co}^2 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2}
\]

\[
\frac{15,934 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} + \frac{15,934 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} + \frac{4,075 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} - \frac{0,615 \cdot S_{co} \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} - \frac{0,784 \cdot S_{co}^2 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8 \cdot m_{fg}^2} = \pi^2 \cdot \rho \cdot d_{id}^4 \cdot \left( \frac{1}{8 \cdot m_{fg}^2} (15,934 + 15,934 \cdot m_{fg} - 0,615 \cdot S_{co} - 0,784 \cdot S_{co}^2) + \frac{4,075}{8} \right)
\]

\[
d_{id}^4 \cdot \left( \frac{15,934}{8 \cdot m_{fg}^2} + \frac{15,934}{8 \cdot m_{fg}^2} + \frac{4,075}{8} - \frac{0,615 \cdot S_{co}}{8 \cdot m_{fg}^2} - \frac{0,784 \cdot S_{co}^2}{8 \cdot m_{fg}^2} \right) = \pi^2 \cdot \rho \cdot d_{id}^4 \cdot \left( \frac{4,075}{8} + 0,125 \cdot m_{fg}^2 \left( 15,934 + 15,934 \cdot m_{fg} - 0,615 \cdot S_{co} - 0,784 \cdot S_{co}^2 \right) \right) = \frac{4,075 \cdot \pi^2 \cdot p \cdot d_{id}^4}{8} + 0,125 \cdot \pi^2 \cdot \rho \cdot d_{id}^4 \cdot m_{fg}^2 \cdot \left( 15,934 (1 + m_{fg}) - S_{co} \cdot (0,615 - 0,784 \cdot S_{co}) \right).
\]

(10)
Therefore, the desired coefficient of aerodynamic resistance of the proposed design of the heat exchanger in the measured range can be calculated by the Eq. 11:

$$
\zeta_{he} = \frac{4.075 \cdot \pi^2 \cdot \rho \cdot f d^4}{8} + 0.125 \cdot \pi^2 \cdot \rho \cdot d_{fg}^4 \cdot m_{fg}^2 \cdot (15.934 (1 + m_{fg}) - S_{co} \cdot (0.615 - 0.784 \cdot S_{co})).
$$

(Were $(m_{fg})$ – is the mass flue gases flow through the site with a heat exchanger, kg/s, $(S_{co})$ – is the compensation hole area in the inner cone, cm$^2$.

Summary
1. The proposed design of the heat exchanger has a low aerodynamic resistance; the pressure loss was $\Delta P_{he} = 27.3 \, Pa$;
2. By utilizing the heat of flue gases in the proposed design it is possible to obtain up to $Q = 3580$ watt per hour.
3. Based on the experimental data processing, a regression equation to determine the pressure loss in the proposed heat exchanger has been obtained and an expression for determining the aerodynamic drag factor of the heat exchanger design in the real range of its operation has been proposed.

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