Bulgarian Chemical Communications, Volume 56, Issue 1 (pp. 21-26) 2024 DOI: 10.34049/bcc.56.1.AESMT23-02

Increasing the energy efficiency of combustion processes using contact economizer systems and finned tube heat exchanger

D. N. Kolev

Institute of Chemical Engineering, Bulgarian Academy of Sciences, Acad. G. Bonchev Str., Bl. 103, 1113, Sofia, Bulgaria

Received: April, 15, 2023; Accepted: February 19, 2024

The increasing greenhouse gas pollution of the environment and the rising costs of energy resources lead to a search for different methods of waste heat utilization. This paper provides a comparison between two efficient methods for waste heat recovery from flue gases. A system with contact economizer CE and finned tube heat exchangers R is proposed. The comparison between them shows that the CE gives significantly better results both in thermal and economic aspects. For small boiler capacities up to 1-1.5 MW it is advisable to use heat exchangers with finned tubes due to their easier operation.

Keywords: heat exchangers, energy efficiency, CO_2 reduction, contact economizer

INTRODUCTION

Increasing energy efficiency is one of the main objectives of the European Union. Achieving this objective will also achieve the accompanying objectives of reducing greenhouse gas emissions and reducing the use of fossil fuels.

The targets set by DIRECTIVE 2012/27/EU OF THE EUROPEAN PARLIAMENT of 25 October 2012 is to achieve a 20% increase in energy efficiency for 2020 and 32.5% for 2030.

In order to meet these objectives, it is necessary to analyse and propose solutions for a more complete use of fossil fuels [1, 2]. This paper aims to compare existing methods of heat utilization of combustion plants such as finned tube systems [3], and contact economiser systems [4] as well as to provide a solution for the ranges in which they are most efficient.

To be able to compare different heat exchangers we first need to know their characteristics, as well as the characteristics of the flue gases they will work with.

The characteristics of the flue gases produced by the combustion of methane at different excess air coefficients are shown further down in the article.

FLUE GASES HEAT CONTENT

When evaluating heat exchanger apparatuses, it is necessary to know the mean temperature difference. The latter is determined from the change of gas heat contents as a function of the temperature. Because of water vapor condensation, the change of gas heat contents at a given temperature difference is approximately proportional to this difference only for temperatures higher than the condensation temperature. The latter depends on the coefficient of air excess λ at which the fuel is burned. Fig. 1 represents the temperature dependence of the heat contents of flue gases obtained from burning of 1 kmol natural gas at various values of air excess λ.

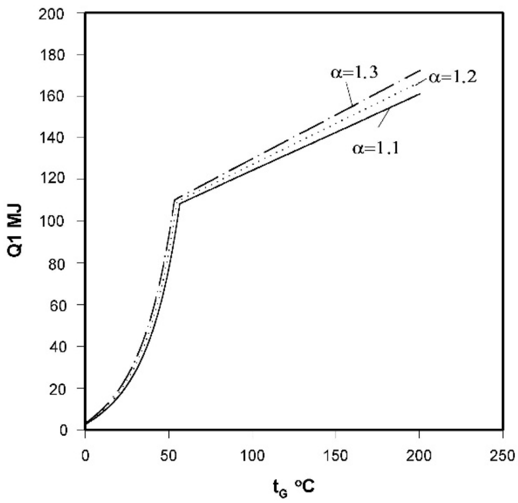

Fig. 1. The heat content of the flue gases, Q obtained from burning of 1 kmol natural gas, as a function of temperature at different values of the coefficient of air excess λ.

Flue gas components are assumed to have ideal gas properties. The temperature dependence of the specific heat at constant pressure Cp is evaluated by the relation:

$$Cp_i = A_i + B_i T + C_i T^2 + D_i T^3, \quad (1)$$

where i refers to the corresponding component; A, B, C, and D are experimental constants for each

* To whom all correspondence should be sent:
E-mail: d.kolev@iche.bas.bg

component, given in [5]; T is flue gas temperature in K.

The enthalpy of an ideal gas mixture of components is expressed as:

$$h_i = A_i(T - 273.16) + B_i(T^2 - 273.16^2)/2 + C_i(T^3 - 273.16^3)/3 + D_i(T^4 - 273.16^4)/4 \quad (2)$$

Eq. (2) is obtained by multiplication of Eq. (1) by dT and its integration in the limits from 273.16 to T.

The results of Eq. (2) for non-condensing components using the constants from [5] were compared with existing data [6]. The error was less than 0.1 %.

Water vapor enthalpy was calculated by Eq. (2) adding also water evaporation heat at 0°C equal to 2500 kJ/kg [6] or 45 000 kJ/kg mol.

Comparing with results from [7] it was found that for the existing conditions an assumption for water vapor as an ideal gas introduces an error not higher than 0.15 %.

The equilibrium partial pressure P, expressed as mm Hg column, necessary for determination of water vapor concentration, was calculated by the relation:

$$\lg P = -2892.369/T + 19.301142 - 2.892734 . \lg T - 4.9369728\times10^{-3} . T + 0.5606905\times10^{-6} T^2 - 4.646\times10^{-2} . T^3 + 3.787\times10^{-12} . T^4 \quad (3)$$

Specialized computer software was developed for determination of the mean temperature difference at given initial and final temperature of the flows.

BRIEF CHARACTERISTICS OF FINNED TUBE HEAT EXCHANGERS

Finned tube heat exchangers can be made in various ways. The most efficient and cheapest are steel pipes with aluminium ribs. They are produced by cold forming of aluminium pipe mounted axially over the steel pipe. Fig. 2 shows a cross-section of the pipe. Substantial advantages of these apparatuses are their high heat transfer ability and low price of about $20 per square meter of heat transfer surface as of writing of this paper.

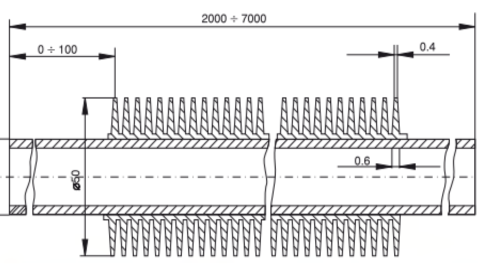

Fig. 2. Cross-section of the finned pipe [8].

An essential shortcoming is the corrosion of aluminium in condensation regime, which does not allow the use of these heat exchangers below the condensation point of the heat-transfer wall. Aluminium doped with magnesium and manganese becomes corrosion resistant to these conditions but is not good for production of ribs over the steel tubes because of its reduced plasticity.

Comparison of various apparatuses should be done at their optimal operating conditions, i.e. at optimal gas velocity. For finned tube heat exchangers, the optimal velocity is that demanding minimum expenses to obtain a desired effect. The expenses are capital and operational. It can be easily calculated that the yearly payment for a 10-year loan will be 20 % of the apparatus price assuming 10 years depreciation period and 15 % interest per year.

The main operational costs are for electricity. The exploitation period is presumed to be 6000 hours per year. The longer this period is, the greater the energy expenses will be. Consequently, the optimal velocity will be lower. On the contrary, the optimal velocity will be higher for a shorter period.

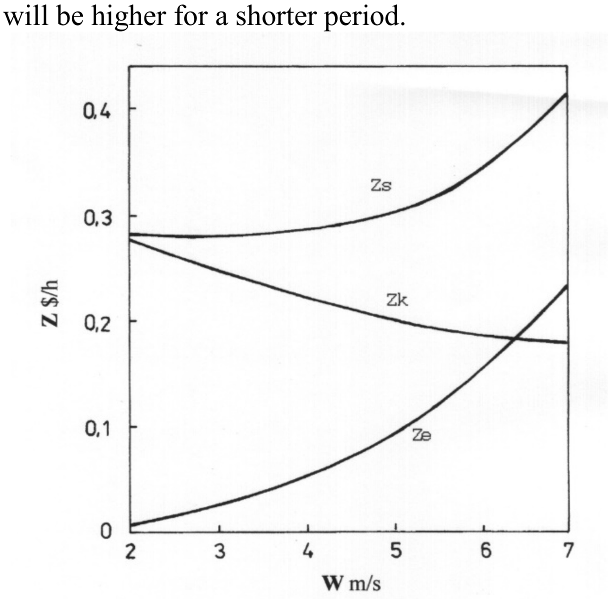

Fig. 3. Dependence of expenses for one-hour operation of an installation with finned tube with aluminium ribs for utilization of 1000 kW waste heat, as a function of gas velocity. Zs-sum of the expenses; Zk – expenses for investments; Ze – expenses for energy consumption.

Fig. 3 shows the expenses for one-hour operation of an installation with a finned tube at various gas flow velocities. Manufacturer's information [8] for heat transfer coefficients and pressure drop under various gas velocities is used to plot the curves. The data is determined under the following additional conditions: initial temperature of heated water 20 °C; final temperature of heated water 55 °C; initial temperature of flue gases 180 ºC; final temperature of flue gases 70 ºC; average temperature 81.85 ºC; estimated at counter-current operation; van efficiency - 60 %; price of electricity – 0.04 $/kWh. The expenses for water feeding are neglected. It is seen that the optimal flow velocity in the free cross-section of the apparatus is 2 - 4 m/s. Since the minimum is not very pronounced, we take the value 4 m/s that corresponds to a smaller apparatus. For this velocity, Fig. 4 supplies the following data: heat transfer coefficient - 24 W/(m^2 ºC); pressure drop - 55 Pa, concerning 2 rows of the finned tube. The mean temperature difference does not essentially affect the optimal velocity. When it increases, the heat exchanger surface is proportionally changed. Consequently, the capital 55 Pa, concerning 2 rows of finned tube costs and pressure drop are also proportionally changed.

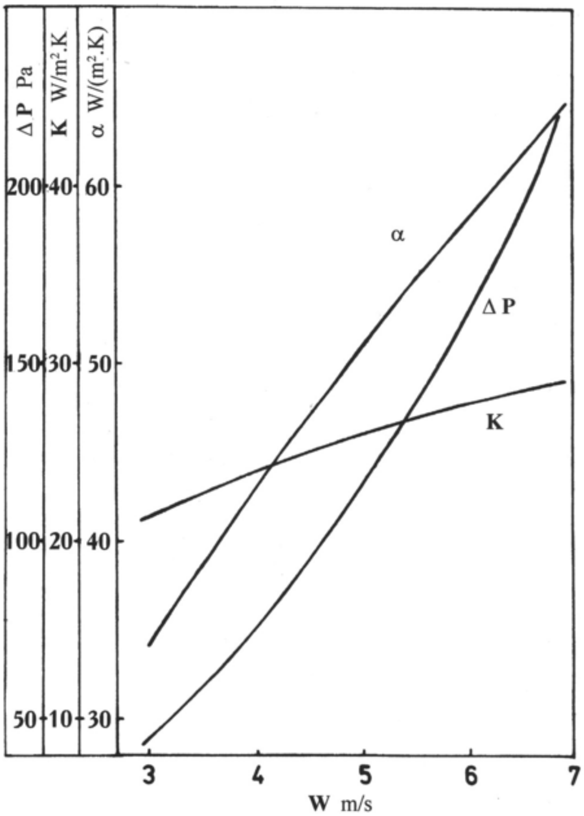

Fig. 4. Dependence of the pressure drop ΔP, K, α as functions of the real air velocity in a heat exchanger with two rows of ribbed pipes arranged in a chess-board order, after data of Klimatech [8].

BRIEF CHARACTERISTICS OF A CONTACT ECONOMIZER

The main quantity of heat in the flue gases, especially when burning natural gas, is the condensation heat of water vapor. The stoichiometric amount of the vapor is 2.25 kg for each kilogram of burned methane. The condensation temperature depends on the apparatus pressure and air excess in the boiler. Normally, it is about 55.5 – 57.5 ºC. The contact economizers systems are created mainly to utilize the condensation heat. Contact economizers utilize heat that can be used mainly for warming of relatively cold flows, such as technical water for feeding of boilers or central heating systems. The maximal temperature of heating is that of the wet thermometer in the flue gases leaving the boiler (about 60 ºC). Profitable heating of water is possible at temperatures of about 4 - 5 ºC lower than that.

A contact economizer system is presented on Fig. 5. The contact economizer system consists of 1 boiler, contact economizer 2, circulating pump 3 and plate heat exchanger 4. Flue gases are scrubbed with circulating water in the packing of the contact economizer 2. As a result, the water is heated and then transported by the pump 3 to the heat-exchanger 4 where it heats a pure water flow. Afterwards the recirculating water is returned to the liquid distributor 5 of the contact economizer 2. The condensed water vapor in the apparatus 2 is evacuated through a hydro-locking device 7. A part of the flue gases can bypass the contact economizer through valve 6.

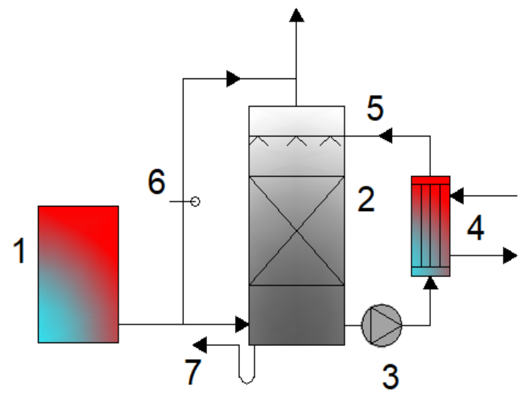

Fig. 5. Technological scheme of a contact economizer system CE [9, 10].

At initial temperature of the flue gases 120 - 130 ºC, the maximal quantity of utilized heat is up to 13 % of the heat produced in the boiler. At 190 - 200 ºC flue gases temperature, the amount of utilized heat is up to 16 %.

The main advantage of a contact economizer system is the extremely high heat transfer coefficient of its plate heat exchanger. It is more than 100 times higher than that of finned tube. Main shortcoming of these systems is the sharp driving force reduction due to adiabatic gas cooling during the initial contact with the circulating water flow.

COMPARISON OF FINNED TUBE HEAT EXCHANGERS AND CONTACT ECONOMIZERS

Finned tube heat exchangers have the essential advantage of being able to heat circulating water flow for central heating purposes, while contact economizers are not applicable for this case. In order to be precise, the comparison between them is made considering the case where both systems can be used - heating of feeding water flow for boilers and for central heating networks. Each of them is able to reduce flue gas temperature to the same value, so capital costs and energy consumption can be compared for equal quantity of utilized heat.

For evaluation of the capital costs, it is convenient to compare apparatus price divided by the quantity of heat utilized for unit of time and unit of temperature difference. It should also be accounted that in the contact economizer about 1°C is lost.

From equation:

$$Q = K.F.\ \Delta t_m \quad (4)$$

it follows:

$$F = Q/(K.\ \Delta t_m), \quad (5)$$

where:

Q [W] is the heat quantity transferred through the heat exchange surface for a unit of time;

F - heat transfer surface;

K [W/(m^2 °C)] is heat transfer coefficient;

Δt_m [°C] is mean temperature difference.

The price Z of an installation for production of 1 kW heat power is:

For finned tube heat exchangers:

$$Z_R = F_R.Z_{1R} = Z_{1R}/(0.001.\ K_R.\ \Delta t_{mR}), \quad (6)$$

where:

K_R=24 [W/m^2.K];

Z_{1R}=20 [\$/m^2].

Subscript “1” refers to 1 m^2; subscript “R” refers to finned tube.

For contact economizer systems “CE”:

$$Z_{CE} = F_{CE}.\ Z_{1CE} = Z_{1CE}/[0.001.K_{CE}.(\Delta t_{mCE} - 1)], \quad (7)$$

where:

K_{CE}=4650 [W/m^2.K];

Z_{1CE}=247 [\$/m^2].

In both cases the price of 1 m^2 heat exchanger surface also includes the price of the accompanying equipment needed for operation.

The coefficient 0.001 is for conversion of values of Q from W to kW.

In the case of a plate heat exchanger, the temperature difference is reduced with 1 °C consumed in the contact economizer.

Price calculations for the finned tube heat exchanger are done assuming it to be made of carbon steel.

If the temperature difference of the plate heat exchanger is 3 °C (i.e., Δt_m = 4°C), Z_{CE} is equal to 17.6 [\$/kW].

For the same Δt_m the price of finned tube heat exchangers made of carbon steel with aluminium ribs is Z_R = 208.3 [\$/kW], which is 12.15 times more than that of the contact economizer system. Consequently, in order to have the same capital costs per unit of utilized heat, a finned tube heat exchanger has to work at a mean temperature difference equal to 12.15 × 4 = 48.6 °C when made of carbon steel pipes with aluminium ribs. It means that it is expedient to use the first type finned tube for cooling flue gases to temperatures of about 49 °C higher than the cooling water temperature. Further cooling should be done in a contact economizer system.

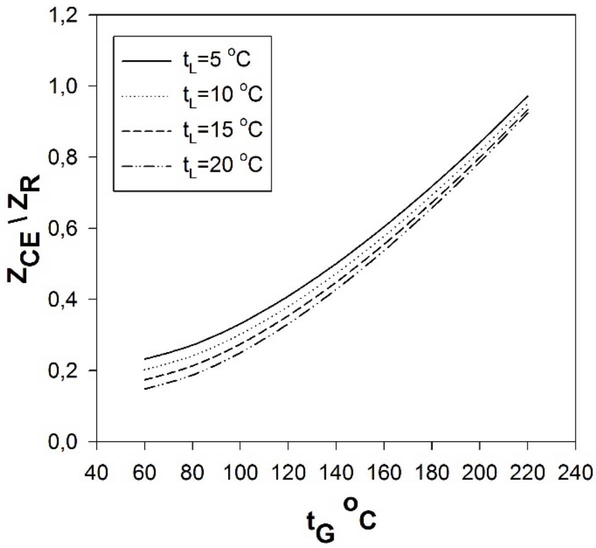

Fig. 6. Dependence of the ratio of the investments Z for constructing CE to the investments for finned tube heat exchangers R at equal quantities of heat utilized from the two systems, as a function of the input temperature of the flue gases, at different values of the input temperature of the water being heated λ=1.1. The temperature of the heated water is 55 °C.

Fig. 6 represents the ratio of capital costs for CE and finned tube heat exchangers utilizing an equal quantity of heat in relation to the gas temperature. Curves for various values of the initial temperature of heated water t_L are shown. The coefficient of air excess is kept constant and equal to λ = 1.1. The mean temperature difference for plate heat exchangers is 3 °C. For finned tube heat exchangers its value is obtained assuming conditions of full counter-current flow, which means that the value Z_{CE}/Z_R is slightly overestimated. The additional conditions used in the calculation of the curves on Figs. 6&7, are stated in the figure captions.

As it was mentioned, finned tube heat exchangers are unsuitable for condensation processes.

The energy consumption for transportation of water flow through both types of heat exchangers is approximately equal and it is not taken into account. For estimation of electrical energy expenses, it is necessary to compare the energy consumption for transportation of gas flow through the finned tube with the sum of energy consumed for gas transportation through the contact economizer and for liquid circulation in the contact economizer system. Gas fans and water pumps have nearly the same efficiency. So, comparison of their theoretical consumption of electricity can be made. Fig. 7 shows the ratio of electric energy consumption for operation of CE and for finned tube heat exchangers at their optimal gas velocity, as a function of the flue gases initial temperature. The curves show various initial temperatures of the heated water. They are obtained using the equations and particular values already given above.

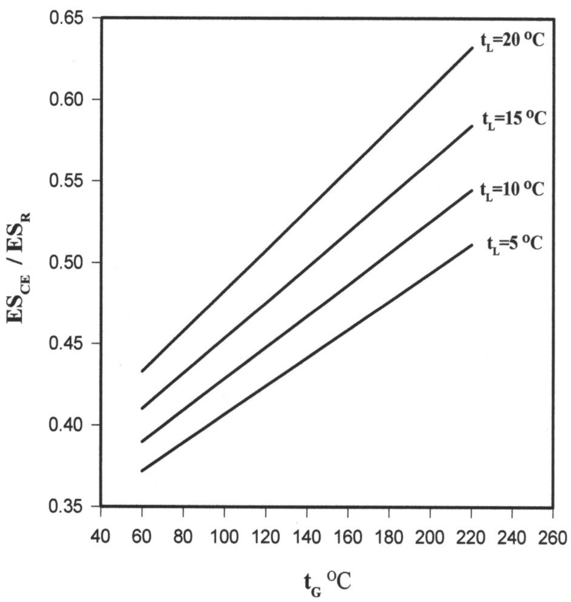

Fig. 7. Ratio of electric energy consumption for operation of CE and for finned tube heat exchanger at their optimal gas velocity, as a function of the flue gases initial temperature t_G at different values of the input temperature t_L of the water being heated.

The water - gas ratio, used for calculation of the liquid phase energy consumption in contact economizers systems, is determined from the heat energy balance.

CONCLUSION

The comparison clearly shows the superiority of the systems with contact economizer over the heat exchangers with finned tubes, both in terms of capital costs and heat recovery.

An advantage of the finned tube heat exchangers, in comparison to contact economizers systems, is their simple technological scheme and simple operation. That is why, in case of small boilers with capacity of 1 - 1.5 MW, where the difference in the efficiency for both types of installation is not too large, it may be better to use the finned tube heat exchangers. It must be considered that condensation of water vapor on the heat exchanger fins leads to corrosion. In Fig. 8 below is a graph with a condensing temperature of 55 °C and an air excess λ=1.1 showing the area in which the finned tube heat exchanger can be used.

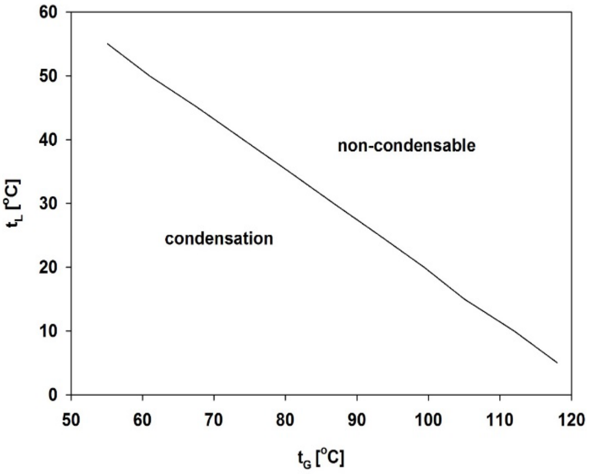

Fig. 8. Curve along which the fin temperature of the finned heat exchanger is 55°C condensation point, t_L is the supply temperature for heating cold water, t_G is the outlet temperature of the boiler operating at an air excess λ=1.1.

INNOVATION

The greatest economic effect would be the simultaneous operation of both apparatuses finned tube heat exchangers and contact economizers. The flue gases first pass through the finned tube heat exchanger 8 (Fig. 9) and then through the contact economizer 2 [11]. The heating water first passes through the plate heat exchanger 4 and then through the finned tube heat exchanger 8. This circuit solution makes it possible to utilise a greater amount of heat than with finned tube heat exchangers, and to raise the temperature of the heated water above the wet thermometer.

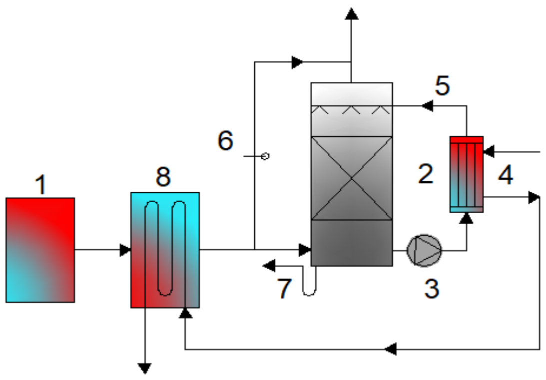

Fig. 9. Technological scheme of the proposed innovation [11]. Boiler 1, contact economizer 2, circulating pump 3, plate heat exchanger 4, liquid distributor 5, bypass valve 6, hydro-locking device 7, finned tube heat exchanger 8.

NOMENCLATURE

A, B, C and D - experimental constants given in [5];

Cp- specific heat at constant pressure, kJ/kgmol;

h- enthalpy, kJ/kgmol;

K- heat transfer coefficient, W/(m^2 ^{o}C);

P- partial pressure of water steam, mm Hg column;

Q- amount of heat in flue gases obtained by burning of 1 kmol natural gas, kJ;

T - flue gas temperature, K;

Z- price of an installation producing 1 kW heat power, \$/m^2;

α - gas-phase heat-transfer coefficient, W/(m^2 ^{o}C);

ΔP – pressure drop, Pa;

Δt_m - mean temperature difference, ^{o}C;

λ- coefficient of air excess.

Subscripts

i refers to the corresponding component;

CE contact economizer;

R ribbed-pipes;

G gas;

L liquid.

REFERENCES

1. I. Iliev, Methods and means for efficient utilization of waste heat from low potential steam-gas streams, Academic Publishing Center of Ruse University “A. Kanchev”, 2023, ISBN: 978-619-90013-9-4 (2013) (in Bulgarian).
2. D. Kolev, N. Kolev, *Applied Thermal Engineering*, **22,** 1919 (2002).
3. M. Yuan, G. Liu, X. Zhang, W. Zhang, Y. Yang, J. Song, H. Chang. L. Lim, *International Journal of Heat and Mass Transfer,* **205**, 1 (2023).
4. D. Kolev, *Bulgarian Chemical Communications,* **35** (3), 153 (2003).
5. R. C. Reid, J. M. Prausniz, T. K. Sherwood, The Properties of Gases and Liquids, Third edn., McGraw-Hill Book Company, ISBN-13978-0070517998, (1987).
6. Chemist’s manual, vol. III, Chemistry, Gosudarstvennoe nauchno - technicheskoe izdatel’stvo khimicheskoi literatury, Moscow, 1964 (in Russian).
7. S. Rivkin, A. Aleksandrov, Thermodynamic properties of water and water steam, Technics, (1978) (in Bulgarian).
8. Klimatech prospect, 8400 Dimitrovgrad, 1 Brodsko chaussee str. (in Bulgarian).
9. I. Z. Aronov, Contact heating of water by burning natural gas, Nedra, Leningrad, 1985 (in Russian).
10. N. Kolev, Kr. Semkov, R. Daraktschiev, *Heat Energetics,* **3** (8, 9), 6 (1990) (in Bulgarian).
11. N. Kolev, D. Kolev, R. Darakchiev, Bulgarian Patent: A method for utilization of heat of humid gases and an installation for its realization, Reg. No. 101 404, April 10, 1997.