UNIVERSITY OF NIŠ
The scientific journal **FACTA UNIVERSITATIS**
Series: **Mechanical Engineering** Vol.1, N° 4, 1997 pp. 447 - 457
Editor of series: Nenad Radojković
Address: Univerzitetski trg 2, 18000 Niš, YU,
Tel: (018) 547-095, Fax: (018)-24-488

AN INFLUENCE OF BOILER-RECOVERY-HEAT EXCHANGER TO BOILER SIZE - A TOOL-SHOP EXAMPLE

UDK: 621.182.3

Milorad Bojić,* Predrag Rašković, and Nenad Radojković*****

*Mechanical Engineering Faculty, Kragujevac University, Sestre Janjić 6, 34000 Kragujevac, Yugoslavia, **Chemical Engineering Faculty, Niš University, Bulevar Oslobodjenja 124, 16000 Leskovac, Yugoslavia, and *** Mechanical Engineering Faculty, Niš University, Beogradska bb, 18000 Niš, Yugoslavia.

Abstract. *In a tool shop, different boilers may provide heat needed by space heating and hot technology. We try to conserve energy by using design solutions with recovery-heat exchangers and optimal sizes of heat-transfer surfaces of boilers. As an optimization methodology we have used sequential linear programming (LP). The LP-objective functions have been the minimum energy and money expenditures. After a design optimization of energy system of our example-tool shop we will have an energy saving up to 5%, and money saving up to 14%.*

1. INTRODUCTION

Many methods for optimization of energy performance of an industrial building [1]-[7] are available. The LP is widely used in energy optimization of steam network, [8], [9] steel mills[10] and refuse heat utilization. [11], [12]. We did not find an application of this method in the field of heat recovery in industrial buildings with boilers as their integral parts.

We use a bottom-up approach and finite time thermodynamics. The energy system of this tool shop is described by an energy-object network [13]. The energy objects are depicted by using linear equations. With obtained mathematical model, we have done simulations and optimizations. During optimizations we have used sequential linear programming. The LP-objective functions have been the minimum energy consumption and minimum money expenditure during the life cycle of energy equipment used in the tool shop. On the basis of this mathematical model we have developed software PCP and PLP1 [14]. We have calculated the optimum sizes of boilers and calculated energy consumption and money expenditure for such design and retrofit solutions. We have

Received January 14, 1997

compared results obtained by solving of optimized and nonoptimized system.

In winter, space heating is needed by a tool shop. Furthermore, if technological processes in the tool shop are hot, heat also is needed for technology. This heat can be obtained by using different heat carriers. The heat carriers can be provided to the tool shop by using different boilers that utilize different fuels.

The tool shop has its boilers. Hot refuse ventilation air and combustion products are available. In such energy system, we may employ these refuse hot gases by using recovery-heat exchangers. In these heat exchangers, the fresh air for air-space heating and fuel mixtures (air plus gas fuel) may be preheated. Then, heat is recovered from hot refuse gases and transferred back to the tool shop.

Our energy system of the tool shop should have all these possibilities for heat recovery. On the other hand, our design solution of such energy system has to provide us that a money expenditure during the life cycle of installed equipment is minimum. If such system is already in operation, then this energy system should be retrofitted so its energy consumption has to be minimum. When, at the same time, there are heat-recovery exchangers and boilers as this is the case for the example-tool shop, then the sizes of boilers may be calculated on circumstance of minimums of energy and money expenditure.

GLOSSARY

- a oxygen percentage in air (%)
- c specific heat (J/kg-K)
- c_N specific heat (J/kmol-K)
- CE energy price (DM/J)
- CR HE price (DM-K/W)
- H_d lower heating value (J/Nm^3)
- M relative molecural mass (kg/kmol)
- m mass-flow rate (kg/s)
- O_{2min} oxygen minimum (Nm^3/Nm^3 of f)
- Q heat (W)
- r latent heat (J/kg)
- r volumetric composition
- t temperature (deg.C)
- tA life cycle of an installation (years)
- TE money expenditure (DM)
- V gas flow rate (Nm^3/Nm^3 of f)
- W moisture content (g/Nm^3 of dg)
- Z size of HE (m^2/(m^{2}K/W))
- λ coefficient of excess air

Subscripts

- a air
- b boiler
- c cold
- co combustion
- cp combustion products
- e environment
- F objective function
- h hot
- i entrance
- m mixture
- n dimensionless
- o exit
- p non-optimized
- tc thermal comfort
- w constant
- j j=1(H_2), 2(CO), 3(CH_4), 4(C_2H_4), 5(C_2H_6), 6(C_3H_6), 7(C_3H_8), 8(C_4H_{10}), 9(CO_2), 10(N_2), 11(SO_2), 12(O_2), 13(H_2O), 14(H_2S)

Abbreviations

CFHE	counterflow HE
CHE	cold fluid HE
dg	dry gases
ESB	electrical steam boiler
f	fuel
GOB	hot oil boiler
GSB	gas steam boiler
HE1	HE for space heating
HE2	HE for space heating
HE	heat exchanger
HHE	hot fluid HE
LP	linear programming
OHE	heat-exchanger module of GOB
RHE	recovery HE
RHE0	RHE (see Fig.1.)
RHE1	RHE (see Fig.1.)
RHE2	RHE (see Fig.1.)
RHE3	RHE (see Fig.1.)
RHE4	RHE (see Fig.1.)
S1	combustion module of GSB
S2	combustion module of GOB
SHE	heat-exchanger module of GSB
TS	hot tool

2. Mathematical model

2.1 Energy-system

Figure 1 shows the energy system. This energy system consists of the tool shop and three boilers producing energy the tool shop needs. Air for space heating of the tool shop is heated in the heat exchanger HE1 by using hot water and in the heat exchanger HE2 by using steam. The steam used in the HE2 is produced by using a steam boiler (GSB) that consumes natural gas. In the HE1, air is heated by using hot water obtained in an electrical steam boiler (ESB).

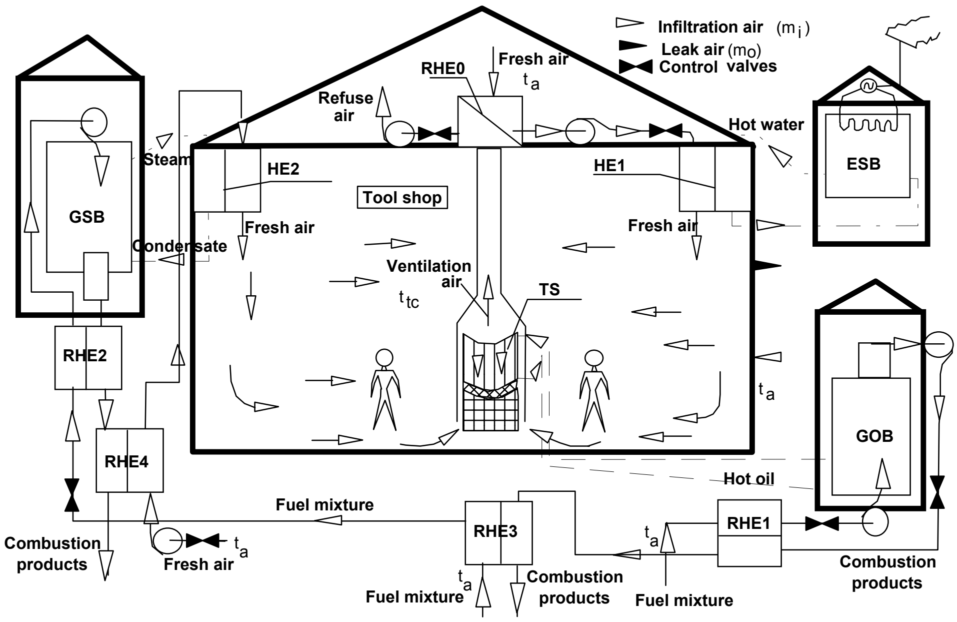

Fig.1. Tool shop with the boilers providing energy to the tool shop.

In the tool shop, (TS), there are hot tools. The hot tools are heated by hot oil obtained from a boiler (GOB) that uses natural gas as a fuel. These tools are ventilated by using space air of the tool shop.

We conserve energy in the tool shop by using five recovery-heat exchangers. The air for space heating, that enters the tool shop via the HE1, is preheated by using the local refuse-ventilation air in the recovery-heat exchanger RHE0. Also, by using the recovery-heat exchanger RHE1, we preheat the fuel mixture (a mixture of air and gas fuel) of the GOB by using its combustion products. By using the recovery-heat exchanger RHE2, we preheat the fuel mixture of the GSB by using its combustion products. Also, the fuel mixture of the GSB is preheated in the recovery-heat exchanger RHE3 by using the combustion products of the GOB. In the recovery -heat exchanger RHE4, the combustion products of the GSB preheat also fresh air entering the tool shop via the HE2.

2.2 Energy-object network

An energy-module network is shown in Fig.2. This network is used for a mathematical modeling of this tool shop. We have used the modules [13] of heat exchangers, combustion, and stream mixing.

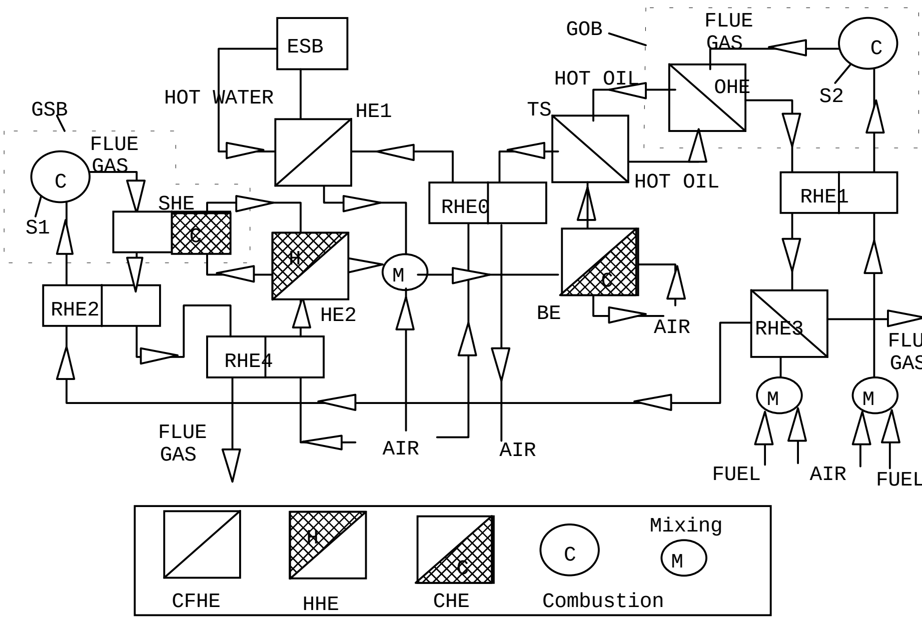

Fig.2. Energy-module network for the tool shop.

The heat-exchanger modules are counterflow (CFHE), cold fluid (CHE), and hot fluid (HHE). The CHE has a constant temperature of colder fluid. The HHE has a constant temperature of hotter fluid. The applied heat exchangers are purely convective with the constant coefficients of total heat transfer.

The general equations governing CFHE, HHE and CHE modules are, respectively,

$$t_{h,o}, t_{c,o}, Q = f(t_{h,i}, t_{c,i}, m_h, c_h, m_c, c_c, Z) \quad , \tag{1}$$

$$t_{c,o}, Q, m_h = f(t_{h,w}\ t_{c,i}, m_c, c_c, Z, r) \quad , \tag{2}$$

$$t_{h,o}, Q, m_c = f(t_{h,i}, t_{c,w}, m_h, c_h, Z, r) \quad . \tag{3}$$

Because we use LP as an optimization method, the equations of these modules are linear. In these heat exchangers instead of logarithmic mean temperature difference, we use an arithmetic mean temperature difference. These equations are given Appendices 1-3.

An exchange of heat from steam to air by the HE2 is defined by using the HHE. A heat exchange from hot water to air in the HE1 is defined by using the CFHE module. The recovery-heat exchangers RHE1, RHE2, RHE3, RHE4 are defined by using the CFHE modules. The tool-shop envelope is defined as a CHE module. In this case, the constant temperature of the colder fluid is the temperature of environment.

The boiler GSB is defined by using the combustion module S1 and CHE module (SHE) where heat is exchanged between combustion products and boiling water. An inlet state of water in the boiler is defined by the enthalpy of hot water at the boiler pressure and its exit state by the enthalpy of steam at this pressure.

The boiler GOB is defined by using the combustion module S2 and a CFHE module (OHE) where heat is exchanged between combustion products and hot oil.

Combustion module is a part of a boiler where combustion of fuel mixture takes place. After a combustion, it is assumed that the combustion products have the theoretical combustion temperature. Gases in a boiler (fuel mixture and combustion products) can be composed by fourteen gas components H_2, CO, CH_4, C_2H_4, C_2H_6, C_3H_6, C_3H_8, C_4H_{10} CO_2, N_2, SO_2, O_2,, H_2O, H_2S. The general equation of the combustion module (Appendix 4) is

$$m_f, m_{cp}, m_a, t_{co} = f\,[r_j\ (j=1,2,..,14), a_i, W_a, \lambda, t_a, t_f] \ . \tag{4}$$

The mass-flow rate and temperature of a gas mixture at the exit of a mixing box are given by using the general equation (Appendix 5)

$$m, t_m = f\,[\ m_j, c_j, t_j\ (j=1\text{-}14)] \ . \tag{5}$$

We have taken here that thermal comfort is a function only of space air temperature. In this investigation, it was taken that the space temperature t_{tc} of the building is constant and provides optimum thermal comfort.

2.3 Objective functions

The first LP-objective functions is the minimum of the energy expenditure

$$Q_F = Q_{GOB} + Q_{GSB} + Q_{ESB} \ . \tag{6}$$

The money expenditure for fuel and energy during the life cycle of this energy equipment

$$\begin{aligned} TE_F = [&CE_G(Q_{GOB} + Q_{GSB}) + CE_E Q_{ESB} + CR_{RHE}(Z_{RHE0} + Z_{RHE1} + Z_{RHE2} + Z_{RHE3}) + \\ &+ CR_{HR}(Z_{HE1} + Z_{HE2}) + CR_B(Z_{OHE} + Z_{SHE} + Z_{ESB})]tA \end{aligned} \tag{7}$$

is the second LP-objective function. Here, CE_G is the price of heat obtained from gas fuel, CE_E the price of heat obtained from electrical energy, CR_{RHE} the unit price of the RHE0, RHE1, RHE2, and RHE3, CR_B the unit price of the OHE, SHE, and ESB, CR_{HE} the unit price of HE1 and HE2 and tA the useful life of the RHE0, RHE1, RHE2, RHE3, HE1, HE2, GOB, GSB, and ESB.

2.4 Dimensionless coefficients

We investigate the dimensionless coefficients

$$(Z_{HE2})_n = Z_{HE2} / (Z_{HE2})_p,\ (Z_{GOB})_n = Z_{GOB} / (Z_{GOB})_p\ , \tag{8}$$

$$(Z_{GSB})_n = Z_{GSB} / (Z_{GSB})_p\ , \tag{9}$$

$$(Q_F)_n = Q_F / (Q_F)_n,\ (TE_F)_n = TE_F / (TE_F)_n\ , \tag{10}$$

The subscript p designates a system which is not optimized.

2.5 Solution procedure

On the basis of this mathematical model we have developed software PCP and PLP1. The software PCP is used for simulation of this energy system. The software PLP1 is used for the energy and the money-expenditure optimization of the energy system.

The equations obtained by using the energy-module network are linearized. For simulation case, we had 26 equations and 26 variables in our model. One of results of this model is the size of Z_{HE2} of the heat exchanger HE2 where are all sizes of other HEs are known. For the optimization case, we had 26 equations and 28 variables. In addition to previous case, new variables were the sizes Z_{OHE} and Z_{SHE} of heat-transfer surfaces of boilers GOB and GSB, respectively. Their values were calculated on the conditions of minimum energy and money expenditure.

3. Results and Analyses

During the first optimization, the energy expenditure was minimum, and during the second optimization the money expenditure was minimum. In all figures, the results of these two optimizations are mutually compared and given as a function of the size of RHE2.

For different size of RHE2 we have obtained the optimal sizes of GOB (Fig. 3.), GSH (Fig. 4.) and HE2 (Fig.5.). For these cases we also found energy expenditure (Fig.6.) and money expenditure (Fig.7.).

Results show that the sizes of the optimized heat-transfer surfaces of GOB, GSB and HE2 differ compared to the non-optimized case. We found that there are energy and money savings. When there is energy optimization we have energy savings up to 5% (Fig.6.) and money savings up to 9%. In the case of the money optimization we will have the money savings around 14% and energy savings of 4.4%.

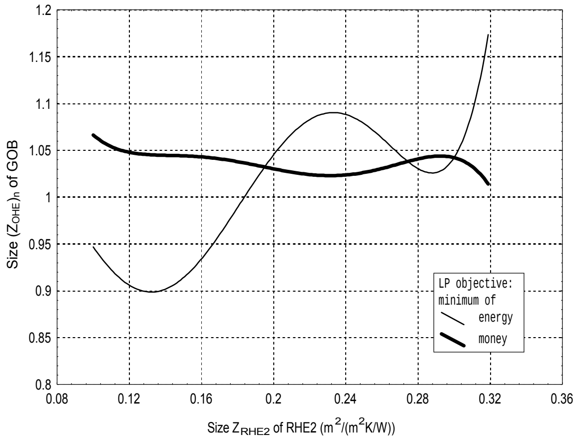

Fig.3. Size $(Z_{OHE})_n$ of GOB as a function of size Z_{RHE2} of RHE2.

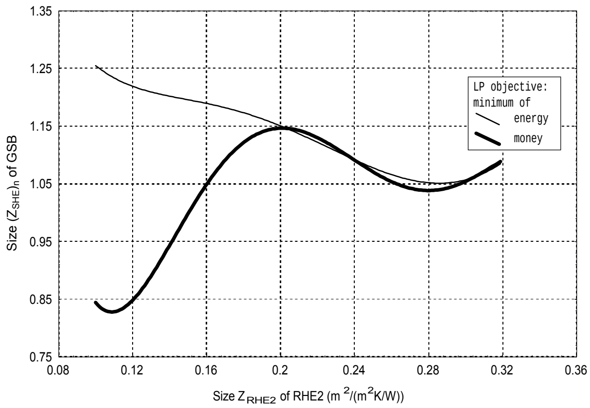

Fig.4. Size $(Z_{SHE})_n$ of GSB as a function of size Z_{RHE2} of RHE2.

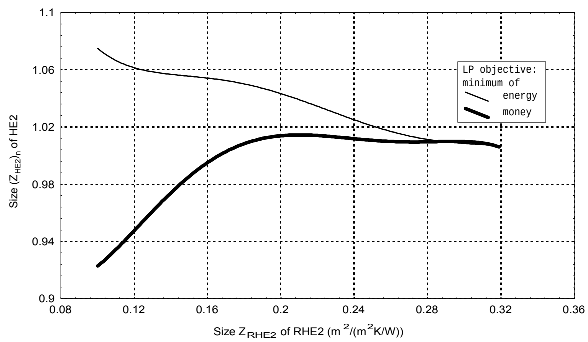

Fig.5. Size $(Z_{HE2})_n$ of HE2 as a function of size Z_{RHE2} of RHE2

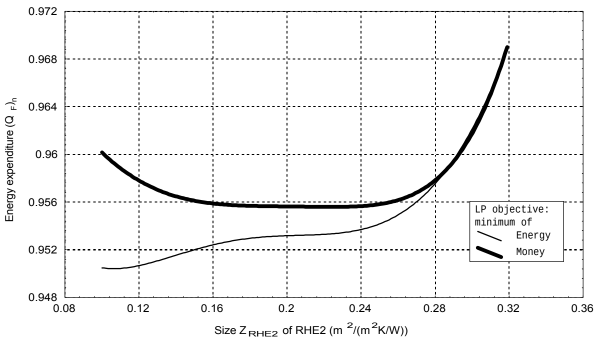

Fig.6. Energy expenditure as a function of size Z_{RHE2} of RHE2.

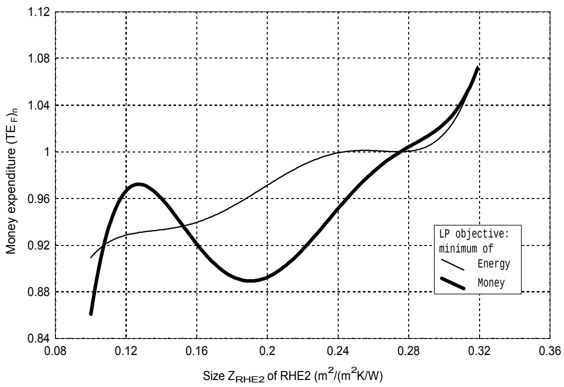

Fig.7. Money expenditure as a function of size Z_{RHE1} of RHE2

4. CONCLUSIONS

When designing an energy system of a tool shop with recovery heat exchangers and boilers, it seems necessary to optimize the sizes of heat-transfer surfaces of boilers to operate with a minimum energy and money expenditure. The money optimization can give better effects than energy optimization. On the other hand, the effects of the money optimization can be uncertain for economies with unstable energy prices.

REFERENCES

1. M. K. Deshmukh, M. S. Sodha, and R. L. Showhney, Int. J. Energy Res. 15, 275 (1991).
2. B. Linnhoff, Trans I ChemE. Chem. Eng. Res. Des. 61, 207 (1983).
3. Y.D. Lang, L.T. Bigler, and I.E. Greossmann, Comput. Chem. Engng 12, 311 (1988).
4. D. Bloomfield, *Building Services* **6,** 13 (1985).
5. E. Hampartsoumian and S. Roser, *Energy World* **4,** 12(1987).
6. A.E. Adderley, P.W. O'Callaghan, and S.D. Probert, *Appl.Energy* **34,** 125 (1989).
7. M.J. Holmes, *Building Services* **8,** 27 (1986).

8. P.L. Goff, *Economies d'energies, de francs ou de devises, Energetique industrielle,* tome 2 Paris (1980).
9. J.K. Clark and N.E. Hemlik, "How to optimize the Design of Stem Systems," in *Process Energy Conservations*, pp.152-164, R. Greene ed., McGraw-Hill, New York, NY (1982).
10. A. Ziebik, *Heat in Industry* **4,** 7(1988).
11. M. Bojić, N.Lukić, and K. Trnobransky, Energy-The International Journal, 20, 1067 (1995).
12. M. Bojić, N. Lukić, and F. Hrdlička, Energy-The International Journal, 21, 1227 (1996).
13. M. Bojić, *Mathematical modeling of Energy Consumption in Industry by using Energy-object-network methodology*, Manual of Process Engineering and technology Series, 8/1996, Process Engineering Publisher, Praha, Czech Republic (1996).
14. P. Rašković, "Optimization of Heat-Recovery Systems in Industry," MS Thesis, Kragujevac University, Kragujevac, Yugoslavia (1996).
15. M. Efros, *Heating and thermal furnaces by using gas fuel* (in Russian), Metallurgia, Moscow, Russia (1965).

APPENDIX 1 - The Counterflow Heat-Exchanger Model with the General Equation

$$t_{h,o}, t_{c,o}, Q = f(t_{h,i}, t_{c,i}, m_h, c_h, m_c, c_c, Z) .$$

When the mass flows m_h and m_c and the temperatures $t_{h,i}$ and $t_{c,i}$ of the incoming streams are known, the temperatures $t_{h,o}$ and $t_{c,o}$ of the exiting streams, and the transferred heat Q are determined by the relations

$$m_c c_c(t_{c,o}-t_{h,i}) = m_h c_h(t_{h,i}-t_{h,o}) , \tag{11}$$

$$Q=Z[(t_{h,i}-t_{c,o})+ (t_{h,o}-t_{c,i})]/2, \tag{12}$$

APPENDIX 2: The Hot Heat-Exchanger Model with the General Equation

$$t_{c,o}, Q, m_h = f(t_{h,w}, t_{c,i}, m_c, c_c, Z, r)$$

The temperature of the hotter stream with the mass flow rate m_h is constant. When the mass flow m_c and the temperature $t_{c,i}$ of the incoming colder stream is known, the temperature $t_{c,o}$ of the exiting stream, the transferred heat Q and the mass flow m_h rate are determined by the relations

$$Q=m_h r , \tag{13}$$

$$Q=m_c c_c(t_{c,o}-t_{c,i}) , \tag{14}$$

$$Q=Z[(t_{h,w}-t_{c,i})+ (t_{h,w}-t_{c,o})]/2 . \tag{15}$$

APPENDIX 3: The Cold Heat-Exchanger Model with the General Equation

$$t_{h,o}, Q, m_c = f(t_{h,i}, t_{c,w}, m_h, c_h, Z, r)$$

The temperature of the colder stream with the mass flow rate m_c is constant. When the mass flow m_h and the temperature $t_{h,i}$ of the incoming colder stream is known, the temperature $t_{h,o}$ of the exiting stream, the transferred heat Q and the mass- flow rate m_c

(if needed) are determined by the relations

$$Q=m_c r\ , \tag{16}$$

$$Q=m_h c_h(t_{h,i}-t_{h,o})\ , \tag{17}$$

$$Q=Z[(t_{h,i}-t_{c,w})+(t_{h,o}-t_{c,w})]/2\ . \tag{18}$$

APPENDIX 4: The Combustion Module with the General Equation

$$m_f,\ m_{cp},\ m_a,\ t_{co}=f\,[r_j\ (j=1,2,..,14),\ a_i,\ W_a,\lambda,\ t_a,\ t_f]\ .$$

The lower heating value of mixed gas fuel, and the minimum quantity of oxygen are

$$H_d=(\Sigma H_{d,j}\, r_j)/100,\ \text{where}\ j=1\text{-}8.14\ , \tag{19}$$

$$O_{2\min}=[0.5(r_{CO}+r_{H_2})+1.5r_{H_2S}+2r_{CH_4}+3r_{C_2H_4}+3.5r_{C_2H_6}+4.5r_{C_3H_6}+5r_{C_3H_8}+ \\ +6.5r_{c_4H_{10}}-r_{O_2}]/100 \tag{20}$$

$$V_{a,i}=100\ \lambda\ O_{2\min}\,/a_i. \tag{21}$$

We have taken $H_{d,j}$ from Ref. 15. The mass flow rates of combustion products, and the volumetric ratios of wet combustion products are

$$V_{cp,CO_2}=(r_{CO}+r_{CO_2}+r_{CH_4}+2\ r_{C_2H_4}+2\ r_{C_2H_6}+3\ r_{C_3H_6}+3\ r_{C_3H_8}+4\ r_{C_4H_{10}})/100, \tag{22}$$

$$V_{cp,H_2O}=(r_{H_2}+r_{H_2S}+2r_{CH_4}+2r_{C_2H_4}+3r_{C_2H_6}+3r_{C_3H_6}+4r_{C_3H_8}+5r_{c_4H_{10}}-r_{H_2O}+ \\ +0.1244W_a\lambda 100O_{2\min}/a_i)/100 \tag{23}$$

$$V_{cp,SO_2}=r_{H_2S}/100,\ V_{cp,O_2}=(\lambda-1)\ O_{2\min}\ , \tag{24}$$

$$V_{cp,N_2}=r_{N_2}/100+(100-a_i)\ O_{2\min}\ \lambda\,/a_i\ , \tag{25}$$

$$V_{cp}=\Sigma V_{cp,j},\ r_{cp,j}=V_{cp,j}\ 100/V_{cp},\ \text{where}\ j=9\text{-}13. \tag{26}$$

The combustion temperature t_{co} is given as

$$t_{co}=(c_f t_f+V_{a,i}\ (c_N)_{a,i}\ t_a+H_d)/[V_{cp}\ (c_N)_{cp}]. \tag{27}$$

The mass flow rate of air m_a and the mass flow rate combustion products m_{cp} are given by the equations

$$m_a=V_{a,i}\, m_f\, M_{a,i}\,/22.4, \tag{28}$$

$$m_{cp}=V_{cp,i}\, m_f\, M_{cp,i}\,/22.4. \tag{29}$$

APPENDIX 5: The Mixing Module with the General Equation

$$m,\ t_m=f\,[\ m_j,\ c_j,\ t_j\ (j=1\text{-}14)]$$

The mass-flow rate and its temperature is given by using the equations

$$m = \Sigma m_j, \tag{30}$$

$$t_m = (\Sigma m_j\, c_j\, t_j) / (\Sigma m_j\, c_j)\ . \tag{31}$$

UTICAJ KOTLOVSKIH RAZMENJIVAČA ZA ISKORIŠĆENJE OTPADNE TOPLOTE NA VELIČINU KOTLOVA - PRIMER HALE SA PRESERSKIM ALATIMA

Milorad Bojić, Predrag Rašković, Nenad Radojković

U industrijskoj hali sa toplim preserskum alatima različiti kotlovi obezbedjuju zagrevanje hale i energiju potrebnu za realizaciju tehnoloških postupaka. Mi smo pokušali da metodom sekvencijalnog linearnog programiranja izvršimo racionalizaciju potrošnje energije projektovanjem više izmenjivača toplote i optimiziranjem veličine površine za razmenu toplote kotlova. Ciljna funkcija metode linearnog programiranja je bila minimalna potrošnja energije sistema i minimalni ekonomski troškovi rada sistema. Po izvršenom optimiziranju energetskog sistema industrijske hale sa preserskim alatima mi smo dobili mogućnost 5% uštede energije i 14% uštede troškova rada sistema.