

Robert Zarzycki (zarzycki@is.pcz.czyst.pl)

Department of Energy Engineering, Częstochowa University of Technology

THE USE OF WASTE HEAT FROM FLUE GAS IN THE SYSTEM OF  
REGENERATION OF STEAM BOILER SUPPLY WATER

WYKORZYSTANIE CIEPŁA ODPADOWEGO ZE SPALIN W UKŁADZIE  
REGENERACJI WODY ZASILAJĄCEJ KOCIOŁ PAROWY

**Abstract**

This study presents an analysis of the process of the use of waste heat from flue gas for the purposes of heating water in the regeneration system of a steam power unit fuelled with brown coal with a power of 900 MW<sub>e</sub>. Preparation of flue gas and its initial moistening (increasing the dew point temperature) followed by cooling (condensation of the moisture contained in the flue gas) can ensure intensive heat exchange in the process of heat recovery. Replacing a first regeneration exchanger with the heat recovered from flue gas allows for an increase in steam power unit efficiency by 0.22% and limitation of CO<sub>2</sub> emissions by 22,810 t/year, while reducing the fuel demand by 26,727 tonnes per annum. Depending on the prices of CO<sub>2</sub> emissions permits and prices of brown coal, the proposed heat recovery allows for saving from €500,000 to €1,000,000 per year.

**Keywords:** waste heat, regeneration system, steam power unit

**Streszczenie**

W pracy przedstawiono analizę procesu wykorzystania ciepła odpadowego ze spalin na potrzeby podgrzewu wody w układzie regeneracji bloku parowego opalanego węglem brunatnym o mocy 900 MW<sub>e</sub>. Po- przez odpowiednie przygotowanie spalin, ich wstępne nawilżenie (podniesienie temperatury punktu rosy), a następnie ochłodzenie (kondensację zawartej w spalinach wilgoci) można uzyskać intensywną wymianę ciepła w procesie odzysku ciepła. Zastąpienie pracy pierwszego wymiennika regeneracyjnego ciepłem pozyskanym ze spalin pozwala na wzrost sprawności bloku parowego o 0.22% oraz ograniczenie emisji CO<sub>2</sub> w ilości 22 810 ton/rok, dodatkowo zmniejsza zapotrzebowanie na paliwo w ilości 26 727 ton/rok. W zależności od ceny uprawnień do emisji CO<sub>2</sub> i ceny węgla brunatnego proponowany odzysk ciepła pozwala na oszczędności od 0.5 do 1 miliona euro/rok.

**Słowa kluczowe:** ciepło odpadowe, układ regeneracji, blok parowy

## 1. Introduction

Electricity and heat in Poland is mainly generated through combustion of hard coal and brown coal. These fuels are burnt in power boilers, mainly pulverized coal-fired and fluidized bed furnaces and allow for production of steam with specific parameters and, consequently, electricity. Efficiency of electricity generation in current industrial power boilers reaches a gross value of 50%, resulting mainly from high initial steam parameters and the scale of the energy sector. There are several investments with an installed capacity of 1,000 MW<sub>e</sub> class currently being implemented (Opole Power Plant, Jaworzno III Power Plant and Kozienice Power Plant). It can be expected that the next power units in the 1,000 MW<sub>e</sub> class are going to be built in the nearest future and replace the obsolete power units built in the 20<sup>th</sup> century that do not meet the specifications contained in the standards concerning emissions. High efficiency of conversion of chemical energy into electricity helps reduce emissions of CO<sub>2</sub> and other harmful substances to the atmosphere. Therefore, further research is needed to improve the thermodynamic efficiency of the electricity and heat generation process in the nearest future. One of the methods to increase the efficiency of the thermodynamic cycle of a system is to improve the parameters of live steam. However, the material needs and the related costs substantially limit the opportunities for improving these parameters. The increase in the thermodynamic cycle efficiency can be achieved through combined generation of electricity and heat.

This study presents investigations concerning the opportunities for using the heat contained in flue gas that leaves the boiler to heat the condensate in the regeneration system.

## 2. Steam power unit

Conversion of the chemical energy contained in the fuel into heat in big energy boilers reaches an efficiency of 85% to 95%. This efficiency depends mainly on the type of the fuel (black coal, brown coal) and the water content in the fuel. The highest amounts of energy in power boilers are lost in the form of flue gas waste. Therefore, several technologies of brown coal drying aimed at limitation of the energy loss are being developed [1–4]. The flue gas waste is caused by the high temperature of flue gas that leaves the boiler and the presence of water steam in the flue gas. In the case of boilers fuelled with black coal, the temperature of flue gas ranges from 120–150°C [5–7], and the flue gas humidity is ca. 0.080 kg/kg [5, 6, 8]. In the case of boilers fed with brown coal, the temperature of flue gas ranges from 160–180°C [5–7], and the flue gas humidity is ca. 0.240 kg/kg [5, 6, 8]. The flue gas temperature depends on the content of water and SO<sub>2</sub> in flue gas.

This study presents investigations concerning the opportunities to utilize the heat of flue gas from a power unit with power of 900 MW<sub>e</sub> fuelled by brown coal to replace the heat of the first heat exchanger in the water regeneration system. Table 1 presents the basic parameters of the steam power unit fuelled with brown coal.

Table 1. Basic parameters of steam power unit fuelled with brown coal

No.	Parameter	Value	
1	Parameters of live steam before the turbine	30 [MPa]; 650 [°C]	
2	Electric power of the power unit	900 [MW <sub>e</sub> ]	
3	Boiler efficiency	90 [%]	
4	Flue gas temperature	170 [°C]	
5	Fuel flow rate	248.35 [kg/s]	
6	Wet flue gas flow rate	1090.2 [kg/s]	
7	Air-fuel ratio	1.2 [-]	
8	Characteristics of fuel in the operational state	Calorific value	7.75 [MJ/kg]
9		Water content	0.5140 [-]
10		Ash content	0.1140 [-]
11		Content of C	0.2320 [-]
12		Content of H	0.0192 [-]
13		Content of O	0.1050 [-]
14		Content of N	0.0032 [-]
15		Content of S	0.0126 [-]
16	Molar fractions of components in wet flue gas	(CO <sub>2</sub> )	0.1211 [-]
17		(SO <sub>2</sub> )	0.0025 [-]
18		(O <sub>2</sub> )	0.0266 [-]
19		(N <sub>2</sub> )	0.5943 [-]
20		(H <sub>2</sub> O)	0.2484 [-]
21		(Ar)	0.0071 [-]
22	Environment parameters	0.1 [MPa]; 15 [°C]; φ = 0.6 [-]	

The diagram of the thermodynamic cycle of the steam power unit is presented in Fig. 1. The system is composed of three turbines: a high-pressure turbine, a medium-pressure turbine and a low-pressure turbine. The supply water regeneration system is composed of four low-pressure heat exchangers and three high-pressure exchangers, and an additional steam attemperator. From the standpoint of heat recovery from the flue gas and using this gas in the regeneration system, one can take into consideration only heat exchangers of the low-pressure section (HE1, HE2, HE3, HE4). The temperature of the condensate that leaves the condenser and feeds the regeneration system is also important from the standpoint of heat recovery. The operational parameters of the low-pressure water regeneration system are presented in Table 2.

The analysis of the operational parameters of heat exchangers presented in the Table 3 can be based on the use of the waste heat from flue gas to replace the operation of the heat exchangers HE1 and HE2. From the standpoint of operation of the steam power unit, the most beneficial solution is to obtain the same parameters in the regeneration system during heat recovery from the flue gas. This will help maintain the operational parameters of other heat exchangers, which has a direct effect on the operation of steam turbine and other regeneration exchangers.

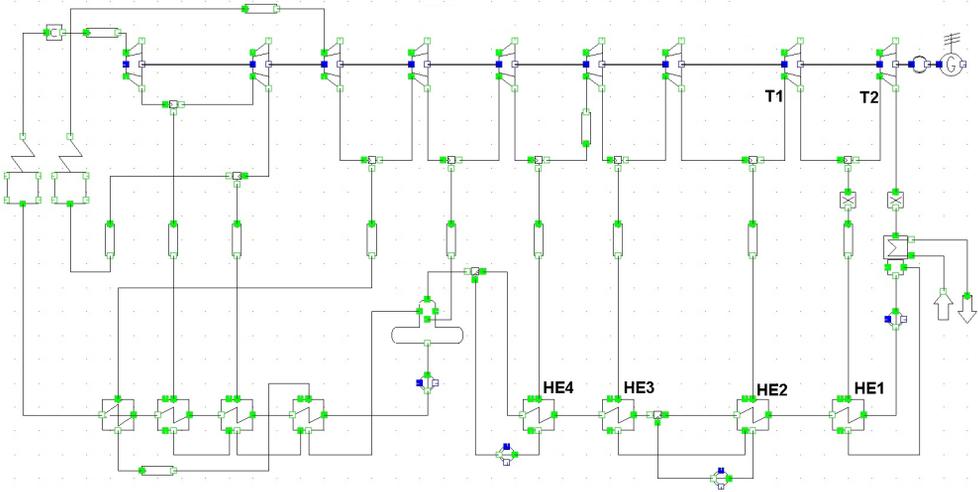


Fig. 1. Diagram of thermodynamic cycle of the steam power unit: case C0

Table 2. Operational parameters of low-pressure heat exchangers

Heat exchanger	Heat power [MW <sub>t</sub> ]	Condensate temperature [°C]		Steam/condensate temperature [°C]		Mass flow rate [kg/s]	
		Inlet	Outlet	Inlet	Outlet	Condensate	Steam
HE1	51.299	33	64	67	67	394.25	22.24
HE2	49.856	64	94	138.1	97	394.25	19.97
HE3	55.123	94.3	124	228.7	127	437.25	23.03
HE4	56.241	124	154	317.8	157	437.25	23.15

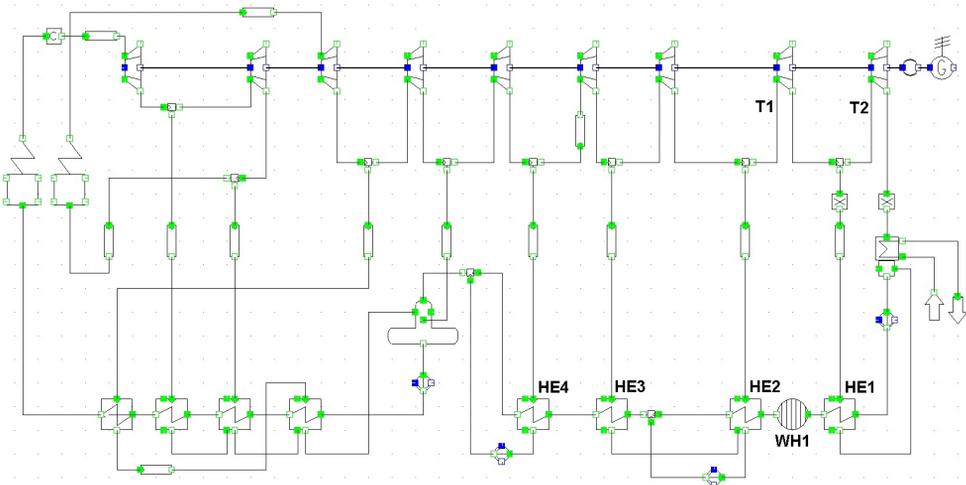


Fig. 2. Diagram of the thermodynamic cycle of the steam power unit with introduction of the waste heat after the heat exchanger HE1 through the exchanger WH1: case C1

Table 3. Comparison of selected parameters of steam power unit before (C0) and after using the heat recovery (C1) by the exchanger WH1

	Case	
	C0	C1
Gross efficiency [%]	46.7029	46.9229
CO <sub>2</sub> emissions [kg/s]	210.21	209.22
Fuel flow rate [kg/s]	248.65	247.49
Boiler heat power [MW <sub>t</sub> ]	1734.363	1726.245
Power of the power unit [MW <sub>e</sub> ]	900	900
HE1 power [MW <sub>t</sub> ]	51.299	0
HE2 power [MW <sub>t</sub> ]	49.856	49.622
WH1 power [MW <sub>t</sub> ]	–	51.058
Steam flow rate T1 [kg/s]	396.6	394.7
Steam flow rate T2 [kg/s]	374.3	394.7
Heat collected in the condenser [MW <sub>t</sub> ]	846.556	889.368

Table 3 presents the results of calculations for the analysed cases of heat recovery from the flue gas for the power unit fuelled with brown coal. Analysis of the data contained in Table 3 reveals that replacement of the operation of the first regeneration exchanger HE1 with the waste heat from flue gas through building the WH1 exchanger (Fig. 2) allows for an improvement in gross electricity generation efficiency by 0.22%. This leads to the reduction of CO<sub>2</sub> emissions by 0.99 kg/s with simultaneous fuel consumption decrease by 1.16 kg/s, which reduces boiler heat power by ca. 8.12 MW<sub>t</sub>. These effects were obtained through replacing the HE1 exchanger with a power of 51.299 MW<sub>t</sub> with heat exchanger WH1 with a power of 51.058 MW<sub>t</sub>. Consequently, the mass flow rate for the stream reaching the turbine T1 declined insignificantly by 1.9 kg/s, which accounts for 0.479% of the nominal flow rate. Due to the exclusion of the exchanger HE1, the flow rate of the steam supplied to the turbine T2 rose by 20.4 kg/s, which is 5.45 % of the nominal flow rate. This led to the increase in flow rate of the heat collected in the condenser by 42.81 MW (5.05% of the nominal heat flow rate to the condenser). After replacement of the heat exchanger HE1 with the waste heat from the exchanger WH1, changes in the operational parameters of the steam power unit reach maximally 5.5% of nominal values, which allows for building this installation without changing the flow in the turbine and condenser.

Due to its high efficiency and fuelling with cheap fuel (brown coal), the power unit of 900 MW<sub>e</sub> size should be operated for the longest possible time with nominal power. With variable daily demand for electricity, it can be adopted that the power unit operates for 16 hours a day with a power of 900 MW<sub>e</sub> and for 8 hours a day with a load of ca. 40%, which means 360 MW<sub>e</sub>. Assuming that the power unit is operated for 8,000 hours a year, the benefits of building the heat recovery installation can easily be calculated. It is possible to reduce CO<sub>2</sub> emissions by 22,810 tonnes per year and the demand for fuel by 26,727 tonnes per year. Based on the above information, the prices of CO<sub>2</sub> emissions permits and prices of brown coal, the economic effect of heat recovery from flue gas can be evaluated. In the scenario “I”,

assuming the price for emissions permits as €5 per tonne of CO<sub>2</sub> and €15 per tonne of brown coal, the savings resulting from reduction in CO<sub>2</sub> emissions are €114,050 per year, whereas the savings connected with reduced fuel consumption are €400,900 per year, which in total yields €514,950 per year. With the scenario “II”, assuming the price of CO<sub>2</sub> emissions permits per tonne of €15 and price of coal of €25 per tonne, the total savings can reach €1,010,300 per year.

Analysis of the above economic benefits should include the necessity of incurring costs for construction of the heat recovery installation and their operating costs. The detailed economic analyses will justify the profitability of building the heat recovery installation. The study presents only the thermodynamic analysis of heat recovery from the flue gas for the purposes of fuelling of the steam power unit.

### 3. Utilization of waste heat from flue gas

The use of the heat recovery presented in the previous section to feed the exchanger WH1 (Fig. 2) requires special preparation of the flue gas. The flue gas that leaves the steam boiler fuelled by brown coal has a temperature of 170°C and contains much moisture that is generated from combustion of the wet fuel and the hydrogen contained in the fuel.

The process of heat exchange between hot flue gas and the water inside the pipes of the heat exchanger is limited by the value of the coefficient of heat penetration for the fuel, which, for forced convection, reaches the values of up to 500 W/m<sup>2</sup>K [9–11], whereas steam condensation for forced convection allows for achievement of this coefficient at the level ranging from 3·10<sup>3</sup> to 2·10<sup>5</sup> W/m<sup>2</sup>K [9–14]. In order to conduct heat recovery from flue gas effectively with the smallest possible size of heat exchanger, it is necessary to utilize the process of steam condensation in the flue gas [15–20]. Condensation of water steam contained in the flue gas also helps clean it from the residue fly ash and other compounds contained in the flue gas e.g. SO<sub>2</sub>, Hg.

For the discussed boiler fuelled by brown coal, the outlet temperature of the flue gas is 170°C, and the water content determines the dew point at the temperature of 64.79°C. The present section discusses the calculations for replacing the first regeneration heat exchanger HE1, where the condensate temperature is 64°C, with a heat exchanger WH1 that recovers heat from flue gas and heats the condensate to 64°C. Despite the high temperature of flue gas (170°C), the extension of the surface is needed for the process of heating water in the exchanger WH1. While increasing the dew point temperature, a high coefficient of heat penetration connected with water condensation can be utilized in the flue gas cooling process. In this case, it is possible to ensure intensive heating of the condensate in the regeneration system to 64°C. Currently designed and manufactured condensation heat exchangers [10, 16, 21, 22] can be operated at the temperature difference between the condensing water steam and water in the exchanger pipes of 3°C.

The diagram of the process of flue gas preparation and heat recovery is presented in Fig. 3. It is composed of the system of flue gas moistening and water condensation with condensate

heating. After cleaning from the fly ash, the flue gas that leaves the boiler is separated into two streams 1 and 4. The stream 1 is supplied to the heat recovery installation, whereas the stream 4, after mixing with the stream 3, is transported to the chimney 10. The flue gas supplied to the heat recovery installation with the stream 1 with temperature of 170°C is characterized by the dew point temperature of 64.79°C, which results from the water content in the flue gas. In order to improve the dew point temperature, flue gas is moistened through spraying the water circulating in the closed cycle of 6, 7. Moistening leads to the reduction in the flue gas temperature in point 2, increasing water content and, consequently, increasing the dew point temperature to 67.22°C. It is necessary to reinforce the stream of circulating water with the stream 5. With the moistening process, flue gas is cleaned of ash, SO<sub>2</sub> and Hg. After this preparation, the flue gas is supplied to the heat exchanger, where it is cooled and the water contained in the flue gas is condensed. The stream 11 is used to remove the condensate. The flue gas is cooled by the water collected after the heat exchange HE1 (8) and supplied before the exchanger HE2 (9) to the temperature 64°C. Table 4 compares selected process parameters of installation of flue gas preparation and heat recovery.

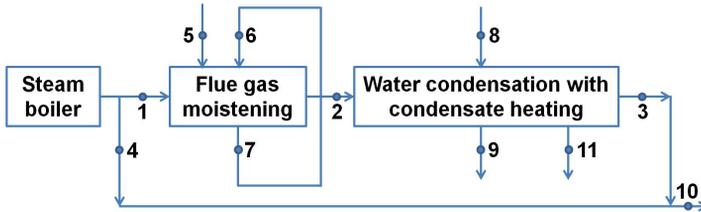


Fig. 3. Flue gas preparation and heat recovery

Table 4. Selected process parameters of installation of flue gas preparation and heat recovery

	Temperature [°C]	Dew point temperature [°C]	Mass flow rate [kg/s]	Water content in flue gas [kg/kg]	Flue gas water content [%]
1	170	64.79	83.51	0.1937	24.84
2	101.9	67.22	85.65	0.2244	27.68
3	36	36	72.55	0.0370	5.95
4	170	64.79	1006.49	0.1937	24.84
5	67	–	2.14	–	–
6	67	–	7.5	–	–
7	67	–	7.5	–	–
8	33	–	394.7	–	–
9	64	–	394.7	–	–
10	160.1	63.95	1079.04	0.1817	23.27
11	36	–	13.1	–	–

For the purposes of the process above, the expected flue gas flow rate that ensures adequate heat flux for condensate heating in the regeneration system amounts to ca. 7.66%

of the nominal flue gas stream. The proposed solution offers more effective utilization of the heat contained in the flue gas for e.g. generation of the system heat for heating purposes or heat for fuelling an absorption cooler used for the production of chilled water.

#### 4. Conclusion

The heat recovery for the purposes of the low-pressure regeneration system allows for improving the gross efficiency of the power unit by 0.22%. This allows for reduction in CO<sub>2</sub> by 0.99 kg/s and demand for the fuel stream by 1.16 kg/s for the nominal power of the power unit. Depending on the prices of CO<sub>2</sub> emissions permits and prices of fuel, it is possible to reach savings ranging from ca. €500,000 to €1,000,000 per year. For the purposes of heat recovery, the use of the flue gas moistening process and cooling with condensation of the water, it is sufficient to collect ca. 7.66% of the total flue gas stream. The use of the process of water condensation helps intensify the process of heat transfer from flue gas to the heated condensate, allowing for a substantial reduction in the size of the heat exchanger. Condensation of water contained in flue gas helps clean the flue gas of fly ash and other water-soluble gaseous components. This also helps recover water from the flue gas.

Apart from the above benefits of the process of heat recovery, one of the drawbacks is high costs of building the condensation heat exchanger as its material has to be resistant to corrosion effect of the condensing flue gas and the gas they contain.

BS/PB-404-301/11

#### References

- [1] Panowski M., Klajny R., *Analiza termodynamiczna wstępnego podsuszania paliwa*, Mat. Konf. XX Jubileuszowy Zjazd Termodynamików, ISBN 978-83-7493-407-7, 2008, 189–193.
- [2] Sławiński K., Knaś K., Gandor M., Nowak W., *Suszenie węgla brunatnego w energetyce – możliwości zastosowania młyna elektromagnetycznego*, Zeszyty Naukowe Politechniki Rzeszowskiej – seria Mechanika, Vol. 86 (3/14), 2014, 2300–5211.
- [3] Pawlak-Kruczek H., Plutecki Z., *Suszenie węgla niskogatunkowego*, Wydawnictwo „Nowa Energia”, 2014.
- [4] Lichota J., Plutecki Z., *Suszenie węgla w elektrowniach*, Rynek Energii, 2007, No. 6, 36–41.
- [5] B&W, *Steam: Its Generation and Use*, The Babcock & Wilcox Company, New York 2007.
- [6] Spliethoff H., *Power Generation from Solid Fuels*, Springer-Verlag Berlin Heidelberg, 2010.
- [7] Chmielniak T., Łukowicz H., *Modelowanie i optymalizacja węglowych bloków energetycznych z wychwytem CO<sub>2</sub>*, Wydawnictwo Politechniki Śląskiej, Gliwice 2015.

- [8] Szulc P., Tietze T., *Odzysk i energetyczne wykorzystanie gazów wylotowych pochodzących z bloków energetycznych elektrowni węglowych*, Materiały VI Konferencji Naukowo-Technicznej „Energetyka gazowa 2016”, Vol. II, Wydawnictwo Instytutu Techniki Ciepłej, Gliwice 2016.
- [9] Incropera F., DeWitt D., *Fundamentals of heat and mass transfer*, 4<sup>th</sup> edition. John Wiley and Sons, 1996.
- [10] Cao E., *Heat transfer in process engineering*, McGraw-Hill, 2009.
- [11] Hobler T., *Ruch ciepła i wymienniki*, WNT, Warszawa 1979.
- [12] Bohdal T., Matysko R., *Analiza kondensacji pary wodnej na rurze pionowej*, Ciepłownictwo, Ogrzewnictwo, Wentylacja, No. 7–8/2004, 35–41.
- [13] Broomley L., *Heat transfer in condensation – effect of heat capacity of condensate*, Ind. Eng. Chem. 44, 1952, 2966–2969.
- [14] Siddique M., Golay M., Kazimi M., *Local heat transfer coefficients for forced-convection condensation of steam in a vertical tube in the presence of a noncondensable gas*, Nuclear Technology 102, 1993, 386–402.
- [15] Colburn A., Hougen O., *Design of cooler condensers for mixtures of vapors with non-condensing gases*, Industrial and Engineering Chemistry, Vol. 26, 1934, 1178–1182.
- [16] Heaphy J.P., Carbonara J., Litzke W., Butcher T.A., *Condensing Economizers For Thermal Efficiency Improvements And Emissions Control*, U.S. Department of Energy No. DE-AC02-76CBOO016, 1993.
- [17] Sparrow E., Lin S., *Condensation heat transfer in presence of a noncondensable gas*, Journal of Heat Transfer, 1964, 430–436.
- [18] Wójs K., Szulc P., Tietze T., Sitka A., *Concept of a system for waste heat recovery from flue gases in coal-fired power plant*, Journal of Energy Science, Vol. 1, No. 1, Wrocław University of Technology 2010, 191–200.
- [19] Chen Q., Finney K., Li H., Zhang X., Zhou J., Sharifi V., Swithenbank J., *Condensing boilers applications in the process industry*, Applied Energy, No. 89, 2012, 22–36.
- [20] Wójs K., *Odzysk i zagospodarowanie niskotemperaturowego ciepła odpadowego ze spalin*, Wydawnictwo Naukowe PWN SA, Warszawa 2015.
- [21] <http://www.radscan.se> (access: 03.07.2016).
- [22] Shi X., Che D., Agnew B., Gao J., *An investigation of the performance of compact heat exchanger for latent heat recovery from exhaust flue gases*, Int. J. Heat Mass Transfer, 54, 2011, 606–615.