VIABILITY ANALYSIS OF HEAT RECOVERY SOLUTION FOR THE INDUSTRIAL PROCESS OF ROASTING COFFEE

by

Miroslav V. KLJAJIĆ [*]***, Aleksandar S. ANDJELKOVIĆ, and Dušan D. GVOZDENAC***

Faculty of Technical Sciences, University of Novi Sad, Novi Sad, Serbia

Original scientific paper
DOI:10.2298/TSCI151013044K

Every industrial heat recovery solution is a specific engineering challenge, not because of the predicted energy rationalization or the achieved energy savings but due to potential unavoidable technological deviations and consequences on the related processes and for sure, due to high investment related to delicate design and construction. Often, the energy savings in a particular segment of the industrial process is a main goal. However, in the food industry, especially roasting coffee, additional criteria has to be strictly observed and fulfilled. Such criteria may include the prescribed and uniform product quality, compliance with food safety standards, stability of the processes etc., and all in the presence of key process parameters such as variability, inconsistency of raw material composition and quality, complexity of measurement and analytical methods, etc. The paper respects all circumstances and checks the viability of the proposed recovery solution. The paper analyzes the possibility of using waste heat from the roasting process to ensure the shortening of the roasting cycle, the reduction of fuel consumption and the increasing capacity of roasting lines on daily basis. Analysis concludes that effects are valuable and substantial, although the complete solution is on the threshold of economic sustainability with numerous opportunities to improve both technical and economic indicators. The analysis combines measuring and analytical methods with standard cost-benefit analysis. Conclusions are derived from measurements and calculations of key parameters in the operating conditions and checked by experimental methods. Test results deviate from 10 to 15%, in relation to parameters in the main production line.

Key words: *industrial coffee roasting, waste heat recovery, solution viability*

Introduction

About 6.7 billion kg of coffee beans are roasted worldwide annually, mostly in batch roasters. Roasting and afterburning uses roughly $11.2 \cdot 10^{12}$ kJ fuel energy per year and causes the emission of roughly $7.0 \cdot 10^{8}$ kg CO_2 per year. Nearly 75% of the heat input to roasters can go out the stack. Part of that heat, *e. g.* the latent heat of the stack-gas water vapour, cannot be readily recovered. Nevertheless, reducing stack-gas temperature or stack-gas mass outflow can reduce fuel energy significantly. Energy consumption for coffee roasters with afterburners can be reduced 30-40% in different heat transferring applications. The feasibility of this ap-

[*] Corresponding author; e-mail: kljaicm@uns.ac.rs

proach is very dependable. Some solutions (afterburner bypassing) can reduce energy use by about 20% [1].

Authors [2] analyzed different solutions for heat recovery from the roasting process, with different assumptions and conditions, and made different conclusions, evaluations and recommendations. Technical feasibility and economic assessment of an air conditioning system for the factory buildings is done. The energy balance of the roasting process confirmed the feasibility of heat recuperation from a high temperature source. However, analysis shows that the energy recovery was not cost-effective for all applications. The economic assessment of the proposed alternatives was carried out using common indexes like pay-back period (results are 7.6-13 years) and IRR (results: 5.74% to 15.65%).

Large energy consuming processes, like industrial coffee roasting, need to consider techniques for reusing unrecovered waste heat losses in exhaust gases for a number of reasons. This is especially important because industrial plants have three essential components required for waste heat recovery: (1) an accessible source of waste heat, (2) a recovery technology, and (3) using possibilities for their covered energy [3]. Waste heat recovery strategies, at moderate temperatures less than 500 °C, are more cost-effective today with the increasing energy prices, technological development by equipment manufacturers, decreasing equipment costs and growing competitive pressure on the market [4]. In industrial utility heat generators, the majority of heat losses are from exhaust flue gas. In order to reduce the exhaust flue gas temperature and further boost the plant efficiency, a heat recovery system could be implemented [5].

In business context, industrial sector shows an increasing interest in the field of waste heat recovery, because fossil fuel supply problems are often combined with the increase in its prices, as well as the need for the consumption and cost reduction [6]. By recuperation of waste heat, the quantity of fossil fuels could be lowered, thereby reducing the fuel costs and increasing the competitiveness of industries [7]. The decision to invest in heat recovery is challenged with many barriers of different nature. Installing additional heat recovery equipment can effect technical improvements, but despite many positive effects, practical limits exist and have to be analyzed carefully [8].

Paper intention

The plant where analysis is done is one of 11 manufacturing units that supply 15 coffee markets worldwide. In all, there is no roasting line with the system for reuse of waste heat as proposed and analyzed in this paper. Only some competing plants have the system with ready-made solutions, for which the supplier of the equipment guarantees only technical and quality parameters, without considering any other aspects. These facts and professional opinions and experiences show that the effects of such installations, almost certainly, do not match the relatively high additional investment, particularly in specific market conditions, as analyzed in the paper.

The proposed solution is not unknown as an engineering idea but it is unknown as experiences about viability and sustainability of solutions for the reuse of waste heat, especially across different aspects (energy, technological and economic), and in conditions in which coffee producer operates (irregular parity of some energy input prices and prices of final products, unsupportive conditions for investments in energy efficiency, undeveloped market of energy services and equipment, *etc.*). In such context, applicability needs to be carefully investigated.

Contribution of the paper is based on reformulated objectives in industrial energy revitalization. Main objectives are the revealing conditions for successful heat recovery, assessing applicability and making corporate-oriented evaluation of the proposed way to reduce energy consumption. The approach involves the viability investigation of heat recovery solution by technical feasibility analysis, following strict technological constrains and challenging economic sustainability. The proposed method is based on real time measurements during the operation of roasting industrial plant and obtained test results in lab conditions. Following technological and economic performances, the proposed method creates additional experiences as a new view on energy rationalization in coffee roasting processes.

Industrial process of roasting coffee

Engineering challenge

Each solution for the improvement of energy efficiency of industrial roasting coffee process, alongside feasibility and continuing effectiveness, has to respect very sensible and significant aspects like: prescribed and uniform product quality, compliance with food safety standards, the necessity of maintaining the stability of the process of preparing raw materials and products, continuation and synchronization of different production lines, applicable temperature ranges, appropriate type of heat exchange at end usage, permitted temperature differentials, *etc*. Additionally, engineering task becomes more complex because of the presence of significant variability of key process parameters, frequent inconsistency of raw material composition and quality, changeability of moisture content *etc*., as well as methodological barriers like lack of analytical calculation methods, complexity of measurement methods in real operational conditions, *etc*.

Improving energy efficiency in industrial plants for roasting coffee, due to the complex circumstances, requires a careful analysis of technical and economic viability and sustainability, through the evaluation of improvement effects like shortening the time of roasting cycle, reducing the need for energy in the roasting process and changing daily line capacity.

The subject of analysis is the coffee roaster, with the capacity of 420 kg of coffee per charge. The idea is to rationalize the energy consumption and increase the capacity of the roasting process through the re-use of waste heat for preheating raw coffee that comes from storage at lower temperatures. In that context, main task is to measure, calculate and evaluate waste heat quantity, quality, and then check availability over time and operating regimes, fouling characteristics of the exhaust line, recover applicability and technological barriers.

Characteristics of the roasting coffee process

The process of roasting green (raw) coffee is a segment of the whole technological process of coffee processing which requires thermal treatment with the use of temperature regime defined in order to achieve the required flavor profile. Roasting takes place in a roaster, driven by natural gas as a fuel. The waste hot gases from the roaster go to the hot cyclone with catalysts. The waste hot gases are treated in the catalyser by oxidation of organic matter in atmospheric oxygen at high temperature (350-400 °C), resulting in decreasing organic matter concentrations. During the roasting process, green coffee in a furnace has to be heated to a temperature of about 205 °C. When the furnace is heated, roasting of one batch takes 12-15 minutes. After this phase, roasted coffee goes into the mixer-cooler, where cooling starts. In the roasting process, a characteristic temperature profile exists, where four characteristic phases of roasting can be identified: preparing for a new roaster filling (heating to the required temperature); input of raw coffee; roasting phase; and water dispensing and output of roasted coffee. Roasting phases differ in energy that is released from the burner, the energy that is delivered to the coffee, as well as the energy contained in the exhaust gas (mixture of gases), and then by the flow (and velocity) of hot gases. Some phases provide gases with different characteristics (temperature, velocity / flow, oxygen content, humidity, particle content, *etc.*), which is necessary to know when analyzing the possibilities of returning the waste hot gases to the roasting process.

Characteristics of coffee as raw material

Sample of testing coffee is a concrete mixture M1, composed by 40% Arabica and 60% Robusta. The characteristics are taken from reports [9-11]. Reported tests were conducted in accordance with the low of the food safety and relevant regulations. Moisture content before roasting is 10.4-11.9%.

Specific heat of raw coffee is determined in accordance with conclusions in reference documents [12-14] where it is measured by calorimetric technique and heat flow at 30 °C. As results of measurement, specific heat of green Arabica is 1.85 kJ/kgK (at moisture content of 7.5%) and specific heat of Robusta is 1.46 kJ/kgK (at moisture content of 4.5%). Authors [13] analyzed the specific heat of various types of raw coffee and determined the variability of the specific heat depending on the moisture content and temperature as follows: Arabica coffee (Mexico) has a specific heat of 0.395 of the specific heat of water; coffee Robusta (Togo) 0.32 and for temperatures up to 30 °C. For temperature between 30 °C and 95 °C, the value of the specific heat should be increased by about 30%.

Figure 1 shows the dependence between the specific heat of mixture M1 and inlet temperature of raw coffee in range 0-30 °C. There is notably less dependence on the inlet temperature (in the range 0-30 °C), while the dependence on the moisture content is slightly larger. Figure 2 shows the linearized literature values of specific heat for the tested range of moisture content [13]. Since the moisture content varies 10-12%, as given in relevant reports [9, 10], the adopted value for the specific heat is 1.726 kJ/kgK.

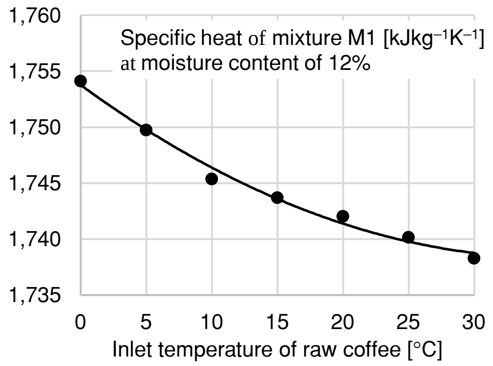

Figure 1. The dependence of the specific heat from the inlet temperature

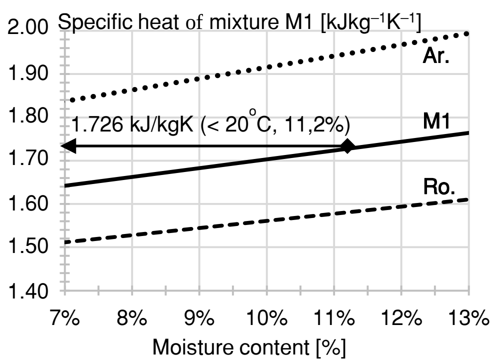

Figure 2. The dependence of the specific heat from the moisture content of raw coffee beans

Proposed improvements of the process

Improving the energy efficiency of the roasting process is primarily related to the reuse of waste heat. Established by measuring method, a significant amount of energy in the hot gases from the roasting process can be used to preheat the raw coffee under certain conditions. In the current technological process, there is no preheating of raw coffee that enters in the roaster storage at temperatures 5-30 °C. This approach requires extra energy to raise the temperature at the time of entrance of raw coffee in the roaster. On the other hand, it was found that the raw coffee can be heated to a maximum temperature of around 100 °C before entering the roaster, without degrading the quality of coffee beans and the final product respectively. By reusing waste heat from the process it can be possible to shorten the roasting cycle, energy savings and changes in the capacity of the line.

Proposal for the new solution suggests a new bunker on the raw coffee transport line at the position directly in front of the entrance into the roaster (fig. 3). This solution provides mentioned necessary conditions for the proper preheating of coffee, with a slight mixing and longer contact of raw coffee beans with heat source. The disadvantage of this solution is the certain plant reconstruction (modification) and development of a new device-mixer and preheater.

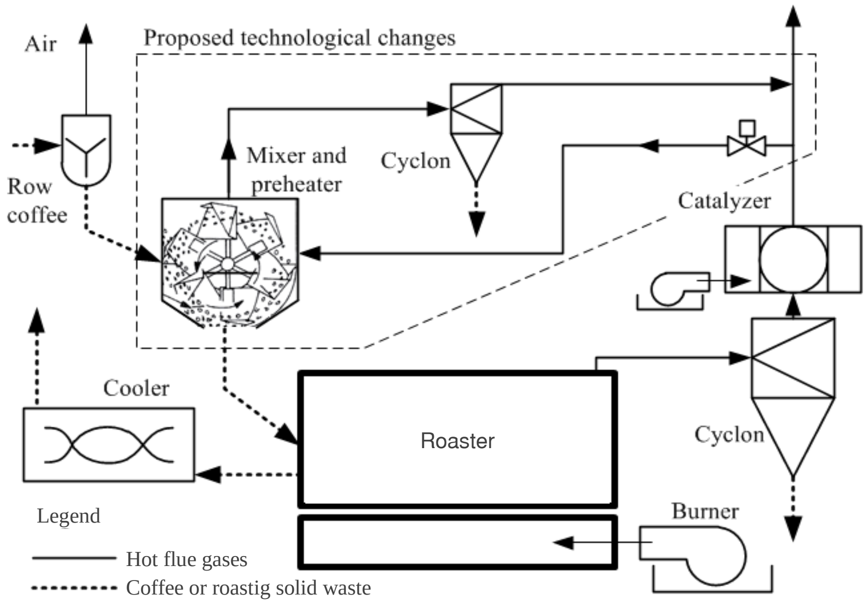

Figure 3. Proposed improvement of the roasting process

Three basic ways of heating raw coffee are considered [15]. Solutions *Preheating in fluidized bed* and *Preheating in fluidized – spouted bed* could have procedural problems related to the inability to control the intensity of the preheating phase and thus the quality control. In addition, these solutions require a larger dimension of the apparatus. Solution *Preheating in the drum with rotating blades and horizontal shaft* is the most appropriate. This design allows for the optimization of preheating because the contact time can be regulated by adjusting the number of revolutions of angles and shapes of blades.

In the proposed process, the preheating time is a very sensitive parameter. Its defining requires two pre-conditions: parallel processes of roasting and preheating and as much as possible lower heat flow and intensity of heat transfer. The main reason is that the short contact of raw coffee with large amount of heat can cause the start of roasting in the most vulnerable layers of coffee fill. The maximum preheating time is 480 seconds, because at that moment of cycle cooling water enters the roaster. That moment is technologically unfavourable and should be avoided in the process of preheating. Preheating time of 450 seconds is suitable because it provides enough heat from the roasting process with the lower intensity of heat transfer. This time provides a gradual and complete preheating of raw coffee and avoids unwanted processes in the grain, which can disrupt the quality of the coffee.

Required thermal energy for preheating

Required thermal energy for preheating is analyzed for charging raw coffee of 420 kg and temperature of 95 ^{o}C. Preheating time of 450 seconds is adopted as the optimal time. Required thermal energy is closely associated with an inlet temperature of raw coffee. By varying the temperature (and input moisture content 10.4-11.9%, as well as the specific heat, which consequently varies), the required thermal energy is determined, as shown in fig. 4.

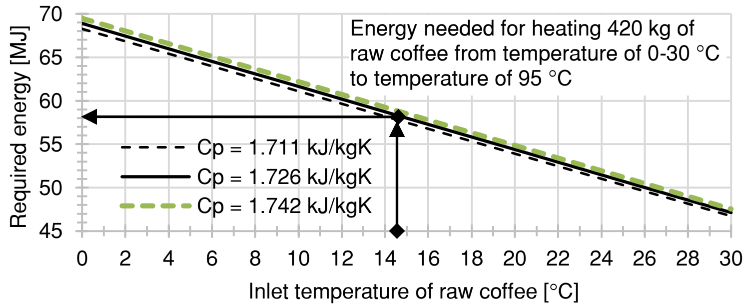

Figure 4. Dependence of required thermal energy and inlet temperature of coffee

By varying the inlet temperature of raw coffee for ±1 °C, the required thermal energy varies for ±1 MJ. The influence of moisture content is low, and the required energy varies 1-2 MJ (1.5-3.5%).

The required heat flow is closely associated with the time of preheating, which is also linked to the preheating intensity. For inlet coffee temperature of 15 ^{o}C and the recommended preheating time (450 seconds), heat flow would be 129 kW ± 0.5 kW. The same procedure is performed for the input coffee temperature of 20 ^{o}C. The results indicate the need for a smaller heat flow which is, for recommended preheating time, 120 kW. Also, one check of the required heat flow is done for the input coffee temperature of 4 °C (preheating time = 450 seconds). The required heat flow is then 145 kW. Two main conclusions here can be drawn: (a) The reduction of the required heat flow is 6-7% for increasing the input coffee temperature for 5 °C, or the maximum reduction is 20-25% for the range of input temperature 10-30 °C; (b) Influence of moisture content in the range 10.4-11.9% does not significantly affect the heat flow; the flow varies 1-2 kW (0.7-1.5%).

Measurement and analysis of the waste heat energy potential

Energy potential of waste heat requires measurements and calculation. For this purpose, energy audit of the production line is done. Some parameters are gathered from automatic readings, but key parameters from the heat source to the heat sink (temperatures, oxygen content, velocities / flows, humidity / dew points) are directly measured in operational conditions and for all regimes. Specification details of the instruments and sensors used for energy audit are presented in tab. 1.

Table 1. Specification details of the measurement instruments and sensors used

Instruments	Specifications
Professional data logger (Testo T4-T177)	4 externals temperature probe: 4 × immersion probes, flexible, Class 1, length 3,000 mm, diameter 1.5 mm. Probe: Thermocouple NiCr-Ni; Resolution: 0.1 °C; Measuring range: – 195 to +1,000 °C; Accuracy: ± 0.5% of measured values.
Infrared thermometer (Testo T845)	Standard focus 60:1; Measuring range: – 30 to +900 °C.; Accuracy: ± 0.75% of mv (– 4.9 to +900 °C); Resolution: 0.1 °C (– 30 to +900 °C.); Spectral sensitivity: 8 to 14 microns; Reaction time: 0.25 s; Setting emission of 0.10 to 1.00.
Gas analyzer (Testo T335)	Measuring range: O_2: 0 to +25 vol%; CO: 0 to 10,000 ppm; NO: 0 to 3,000 ppm; Temperature probe type K (NiCr-Ni): – 40 to +1,200 °C; Accuracy: O_2 ± 0.2 vol%; CO ± 10 ppm; Probes: Gas flow probe and PITOT tube.
Differential Thermometer (Testo T922)	Specifications: Probe: Thermocouple NiCr-Ni (2 channel, type K / J / T); class 1, 300 mm long, Ø 1,5 mm, Response 2 s. Measuring range: – 50 to +1.000 °C; Accuracy: ± 0,7 °C (– 40 to +900 °C); Resolution: 1 °C (+200 to +1,000 °C).

Existing and accessible heat flow during the roasting process

Consumption of natural gas and delivered thermal energy vary from stage to stage of the roasting cycle and the analysis is performed for few characteristic segments of process that differ in operation mode of the burner. The results of heat flow measurements and calculations are associated with the delivered thermal energy in a particular segment of the roasting cycle. The analysis indicates that the enthalpy of hot flue gases = 356.85 kJ/kg. In detailed calculations, variation of enthalpy is 330-430 kJ/kg based on measured and averaged input parameters of hot flue gases (temperature 280 °C; O_2 content by volume 18.23%; 20 ppm of CO and pressure of 1,013 mbar).

Heat losses in the distribution and transfer of energy to raw coffee are roughly calculated, because this information is highly dependent on, at the moment, unknown design characteristics of device for preheating, its performances and operating parameters/regimes. Calculated losses are 30%.

Existing and accessible heat flow that could be reused is considered per duration of characteristic process segment (for instance 100 seconds) and the whole period of preheating. Figure 5 shows thermal energy during the roasting process after the flow rate splitting of 50% and 30% distribution losses.

Figure 6 shows the results of measuring the oxygen content and temperature of flue gases, while gas velocity and calculated values (enthalpy and heat flow) are shown in figs. 7 and 8. All values are displayed in a specific phase of the process, when sampling and measurements are done.

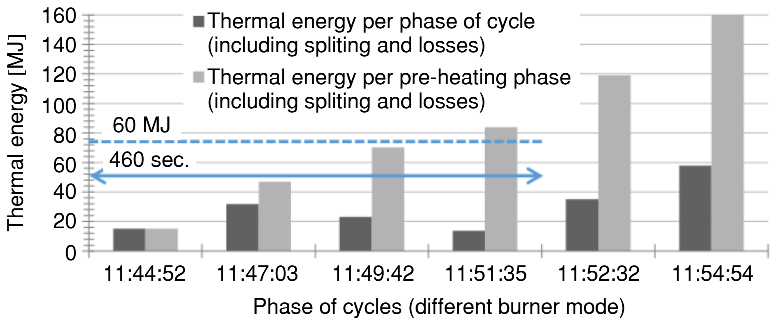

Figure 5. Existing and accessible thermal energy during the roasting process

Enthalpy of the flue gas is determined by the expression: $h = c_{\mathrm{pdg}}\, t_{\mathrm{g}} + d\,(2500 + 1.93\, t_{\mathrm{g}})$, [kJkg$^{-1}_{\text{dry gas}}$], where c_{pdg} is dry gas specific heat capacity, [kJkg$^{-1}_{\text{dry gas}}$K^{-1}]; t_{g} is flue gas temperature, [$^{\mathrm{o}}$C]; and d is flue gas moisture content, [kgkg$^{-1}_{\text{dry gas}}$]. Heat flow of flue gas is calculated using the following expression: $Q = v\rho F h$, [kW], where v is velocity of flue gas, [ms^{-1}]; ρ is density of flue gas, [kgm^{-3}]; and F is cross-section area of the exhaust line, [m^2].

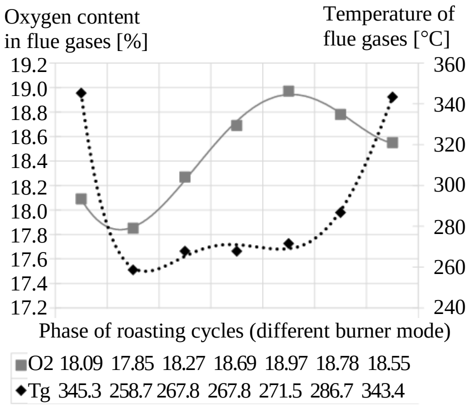

Figure 6. Measured oxygen content and temperature in the exhaust line of the roaster

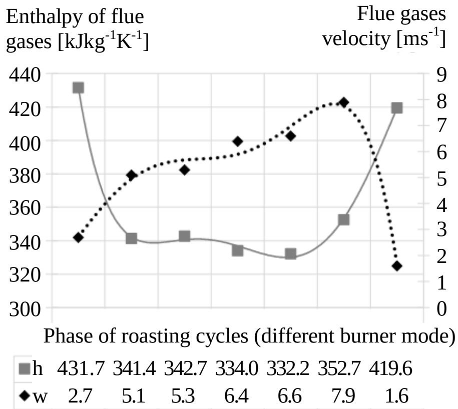

Figure 7. Measured velocity and calculated enthalpy in the exhaust line of the roaster

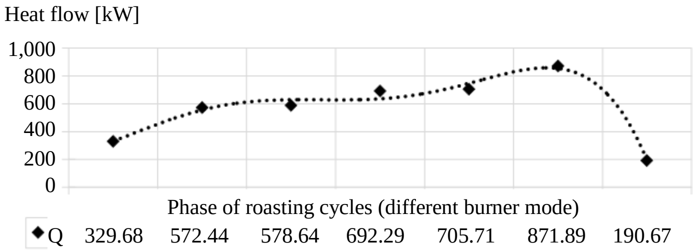

Figure 8. Heat flow in the exhaust line of the roaster

Effects of waste heat reusing

Results of the analysis (tab. 2) indicate the possibility of three effects: (a) Reducing the cycle time of roasting, (b) Reducing energy needs in the roasting process, and (c) Changes in the daily capacity of the roasting line. Since the load of the burner depends on the inlet coffee temperature, the analysis of the effects is done for temperatures 5-30 °C and the moisture content of 11.2%.

Table 2. Effects of reusing waste heat for preheating, for one roasting cycle

Inlet coffee temperature	Energy input for preheated coffee	Reducing energy needs	Reducing regular cycle time		Reducing natural gas consumption	
[°C]	[kJ]	[%]	[s]	[%]	[m^3]	[%]
5	65,258	16.2	113	12.7	2.30	16.2
10	61,632	15.3	106	12.0	2.17	15.3
15	58,007	14.4	100	11.3	2.05	14.4
20	54,381	13.5	94	10.6	1.92	13.5
25	50,756	12.6	88	9.9	1.79	12.6
30	47,131	11.7	81	9.2	1.66	11.7

Shown analysis indicates the increase in savings for the period of the year when the raw coffee is at the lower storage temperature 10-15 °C. In winter, energy savings could exceed 15 or 16%. The effects for the temperatures 5-30 °C and moisture content of 11.9% are also analyzed. The savings increase slightly (by 0.1-0.2%) by the increase of the moisture for 11.2-11.9%. It may be noted that the moisture content does not significantly affect energy savings.

Summary of key comments and findings

- For the adopted annual average temperature of raw coffee 20 °C and moisture content 11.2%, energy savings is 13.5%. Shortening of the roasting cycle (roasting time reduction) is 10.6%.
- Capacity of roaster: for two shifts (16 hours per day) theoretically it is possible to do continuously 64 cycles (average cycle time with the preparation phase is 892 seconds). With the average shortening of the regular cycles by 94 seconds, it can be possible to achieve 72 cycles per day or 8 cycles more per day.
- For the single charge of the roaster of 420 kg, daily capacity would be increased by 3,360 kg per day (from 26,880 kg per day to 30,240 kg per day), assuming that the plant operates in 2 shifts per day.
- For the increased number of roasting cycles and new - reduced amount of required natural gas (approximately 2 m^3/cycle), saving is 138 m^3 per day (work in 2 shifts per day). Avoided costs for energy are 63 € per day. For the manufacturer production, the dynamic of average 15 days per month, possible monthly costs savings is 950 € or per year this is 11,400 €.

Experimental validation of results

In order to validate the results obtained by energy audit, measurements and calculations, the experimental preheating is performed for smaller amounts of coffee in the testing roaster, intended for the product development and research. In fig. 9, the approach for experimental validation is shown.

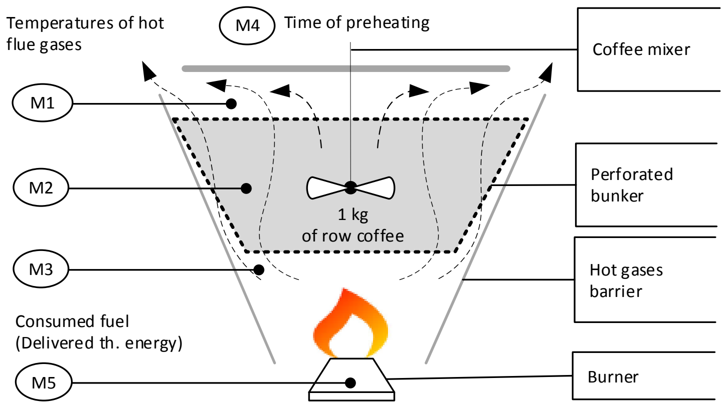

Figure 9. An approach for experimental validation

Experimental validation is done in the manufacturer research centre, where conditions are strictly controlled. The experiment includes the monitoring of delivered energy to the coffee sample and the effects on reducing the roasting cycle. In this way, the simulation of the reuse of waste heat is done in order to examine and evaluate the assumed effects, based on measurements and calculations. Figs. 10 and 11 present the key test results : saved energy based on pre-heating and cycle shortening regarding the process without pre-heating.

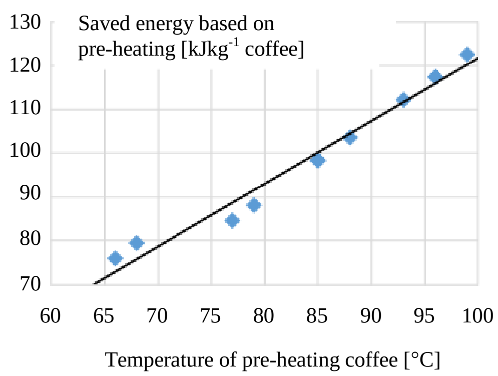

Figure 10. Saved energy

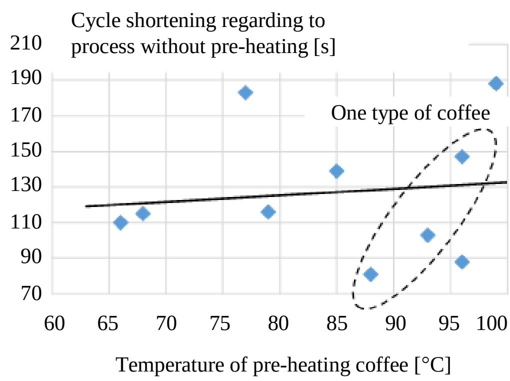

Figure 11. Cycle shortening

From experimental validation and the obtained testing parameters, presented in figs. 10 and 11, the following comments can be drawn:

(1) Every 5° C, increased in the preheated coffee, provide an increase substituted energy in the range of 6-8%, or 6-8 kJ/kg$_{\text{coffee}}$ (average of 7.2 kJ/kg$_{\text{coffee}}$), which represents 3,024 kJ per charge of roaster, or about 0.8% of the total energy needs for roasting one charge. For Δt = 80 °C, saving is 12.8% per roasting cycle. This value corresponds to the real operating measurements and calculations, which determine the average savings of 14.4% per roasting cycle (deviation = – 11%).

(2) Every 5 °C, increased in the preheated coffee, provide an increase substituted energy of ~0.11 Sm^3 of natural gas (in the existing combustion conditions), or an average of 1.76 Sm^3/cycle roasting (for Δt = 80 °C). This value corresponds to the real operating measurements and calculations, which determine the average fuel savings of 1.92 Sm^3/cycle of roasting (deviation = – 9%).

(3) Reducing the cycle time slightly varies (120-130 seconds) for all range of preheated temperature. These averaged values correspond well to the real operating measurements and calculations.

(4) Deviation of values, obtained by experimental methods, in relation to the calculations is:
   (a) energy savings (obtained experimentally) is lower than the calculated by ~10%;
   (b) reducing cycle time of roasting (obtained experimentally) is greater than the calculated by ~15%. The results can be assessed as acceptable considering certain specifics of the high capacity roasting facility and small test roaster (different Δt of raw coffee, fuel used, type of burner, losses of roaster, settings, *etc.*).

Economic projections and feasibility analysis

Cost benefit analysis (CBA) is carried out, for the economic project life of 20 years. Market price of natural gas is used in analysis, where inflation is excluded. This price is adjusted in relation to the base, year 2015, by applying a constant growth rate per year (price escalation factor of 3%).

Investment costs of installation may vary depending on concrete solutions, suppliers, quality of used materials, type of instrumentation, auxiliary equipment, automation, software, *etc.* Direct costs (25,750-50,625 €) include: preheater - mixer with cyclone, piping and fans, instrumentation, electrical and regulation equipment. Indirect costs (15,450-30,375 €) include: integration in supervisory control system, installation, adjustment, testing, adapting infrastructure, cost of project management and documentation, acceptance test, commissioning, *etc.* Periodical, annual costs: control procedures, performance monitoring, maintenance, *etc.* The total initial costs then vary from 41,200 € (Scenario – minimum costs: usual market prices) to 81.000 € (Scenario – max. costs: top quality and reputable designer and engineering). The source of financing is *own funds*.

Economic projections are made for three scenarios: lower costs (Smin.); high costs (Smax.); expected costs (averaging first two assessments – Sav.). Presented methodology uses net present value method and discount rate of 7%, for period up to year 2035. Present value of money over 20 years is positive in each scenario and the project can be considered as cost-effective. Figure 12 shows accumulated net present value and discounted payback period. Table 3 shows key economic indicators.

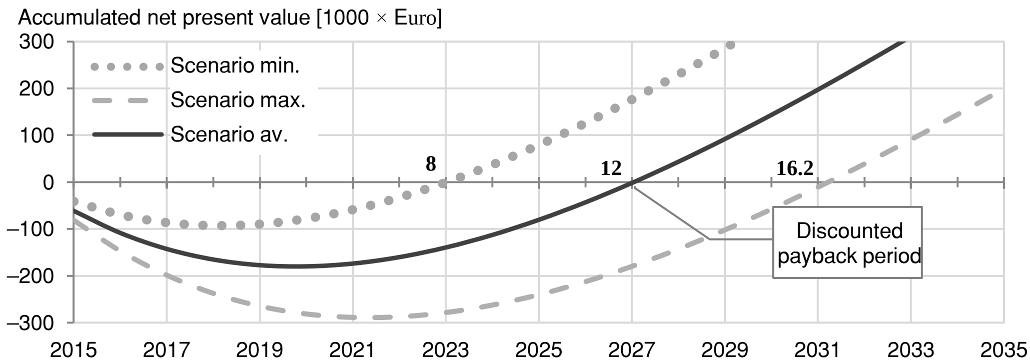

Figure 12. Accumulated net present value for the investment options

Table 3. Summary of economic indicators

Economic indicators Scenario:	Sav.	Smax.	Smin.
Investment (including indirect costs) [€]	61,100	81,000	41,200
Avoided costs for energy (saved energy) per year [€ per year]	11,400	11,400	11,400
Simple payback period, SPB [year]	5.36	7.11	3.61
Discounted payback period, DPB (disc. factor = 7%) [year]	12.04	16.31	8.02
Internal rate of return, IRR [%]	17.8%	11.3%	28.2%
Net present value, NPV [€]	60,212	55,070	65,355
Net present value coefficient, NPVQ [–]	0.99	0.68	1.59

Sensitivity analysis

The most sensitive parameter or the parameter with high risk of achieving is annually achieved savings in energy costs (avoided energy costs). This parameter is dependent on human and technical factors and has a significant impact to economic indicators. For this reason, the analysis has checked the deviations (tab. 4) by expected variations in input parameters, such as price of natural gas, reducing natural gas consumption per roasting cycle, and number of working days of the production line per month. The sensitivity analysis includes checking the sensitivity of key economic indicators (tab. 5).

Table 4. Sensitivity of avoided energy costs [€/a.]

Temperature of row coffee [°C]	Reduction of fuel consumption [m^3 per cycle]	Natural gas price [€/m^3]				
		0.38	0.42	0.46	0.50	0.54
10	2.17	10,570	11,745	12,920	14,094	15,268
15	2.05	9,948	11,054	12,160	13,265	14,370
20	1.92	9,327	10,363	11,400	12,435	13,472
25	1.79	8,705	9,672	10,640	11,606	12,574
30	1.66	8,083	8,981	9,880	10,777	11,676
	Number of working days of line per month	Natural gas price [€/m^3]				
		0.38	0.42	0.46	0.50	0.54
For the reduction of natural gas consumption 1.92 m^3 per cycle	13	8,083	8,981	9,880	10,777	11,676
	15	9,327	10,363	11,400	12,435	13,472
	17	10,570	11,745	12,920	14,094	15,268
	19	11,814	13,126	14,440	15,752	17,064
	21	13,057	14,508	15,960	17,410	18,860

From the presented analysis, the following conclusions can be drawn:

(a) By increasing the price of natural gas for 10%, savings in energy costs will increase for approximately 9%;

(b) By increasing the number of production working days for 10%, savings in energy costs will increase for approximately 12%.

Table 5. Sensitivity analysis of payback periods

Simple / Discounted payback period [year]	Avoided energy costs [€ per year]		Total investment [€]		
			41,200	61,100	81,000
	-10%	10,260	4.02 / 8.98	5.96 / 13.52	7.89 / 18.23
		11,400	3.61 / 8.01	5.36 / 12.03	7.11 / 16.21
	+10%	12,540	3.29 / 7.22	4.87 / 10.84	6.46 / 14.57

Conclusions from the sensitivity analysis are the following: the increase in avoided costs for energy by 10% lowers SPB for 10% and lowers DPB for approximately 10%; after the increase in avoided costs for energy by 10%, IRR increases approximately 12%. Almost the same dependence and trend of changes are present with the variation of investment. Following the increase in avoided costs for energy by 10%, NPV increases approximately 12%. The volume of changes with the variation of the investment is insignificant (below 2%); increase in avoided costs for energy by 10% increases NPVQ by 12%.

Viability assessment

The roasting process with the incorporated heat recovery system has been commercially available for several decades. However, it is only used in a relatively small fraction of the installation. The main reason is numerous barriers that have key influence to the viability of solution. Consequently, the viability has to be discussed and evaluated across the wider assessment of various aspects and different nature of influence factors. Viability assessment is done for the mentioned parameters and following aspects.

(a) Considered basic technical and economic indicators are:
- The heat flow from process (575 kW) > the required heat flow (120-145 kW).
- Economic indicators (SPB: 5 ± 2 year; DPP: 12 ± 4 year; IRR: 11-28%; NPV < 65.000 €).

(b) Some proposed scenario results in relatively long payback periods.
- Higher costs of heat recovery equipment, auxiliary systems and design services.
- Application requires more costly materials for pipes, cyclones and other components. Composition and temperature ranges require better mechanical and chemical properties.
- Equipment costs decrease in large scale heat recovery systems and create challenges for small scale operations like in the proposed case.
- In concrete industrial facility, no other onsite end use opportunities for heat exist.
- The heat flow in this industrial roasting process can vary dramatically and create the mechanical and chemical stress in equipment, increasing the cost.
- Preheater has to work at lower heat transfer rates, increasing dimensions and weight of device.

(c) Proposed solution has a good heat source accessibility and transportability characteristics:
- There is no limitation of physical space where necessary infrastructure needs to be accessed.
- Transportability of waste heat gaseous stream to and through equipment is good and does not require additional energy input (appropriate velocity and flow is available).
- Accessibility to heat sources, such as hot flue gases streams and related equipment, is correct and there are no difficulties because of the existing platform and other elements of building construction.
- Safety and operational demands, that require access to high temperature equipment, are fulfilled.

(d) Roasting process is a specific application with many procedure constraints:
- Equipment designs are process specific without adaptation. Proposed solution is independent, only the preheater is the connection point between the existing and the new part of installation.
- Heat recovery will not complicate and compromise process/quality control. Process control will be slightly upgraded with few simple and independent control loops (regulation of flue gases flow according to inlet temperature in the preheater and time scheduling of charging the roaster).
- Composition and temperature ranges of waste heat stream are favourable (low chemical activity), guaranteeing the chemical compatibility with recovery equipment materials, which is chosen according to standards (advanced recovery equipment materials for concrete environments).
- Deposition of substances on the recovery equipment surface cannot reduce heat transfer rates and efficiency, because of cyclones and catalysis, and rich experiences of staff with this problem.
- Maintenance costs are increased reasonably, primarily due to the existing developed procedures at the entire plant, and also because of low chemical activity of streams (consequently, low damage of equipment surfaces that could lead to the increased maintenance costs).
- Environmental influence and abatement equipment will not be changed (waste heat recovery solution will not complicate or change the control of environmental performances).
- Exhaust streams are physically and chemically compatible (cross contamination is not possible).

Conclusions

Summarized findings indicate that the feasibility of the proposed heat recovery solution is evident. Also, technical and economic viability exists and sustainability could be expected. However, few influence factors could substantially change the effectiveness and viability of the proposed heat recovery solution. Sensitivity analysis reveals the risk of achieving annual savings in energy costs and consequently the variation of economic parameters.

Taking into consideration only three key influence factors (level of investment, production volume and market price of natural gas), it can be concluded that there is a moderate to good technical and economic viability of the proposed system for the reuse of waste heat.

Dependence and influence are discussed by thresholds of solution viability, as follows:

- The investment (evident viability < 55,000 € > moderate to weak viability); Investments 60,000-80,000 € should not be dismissed, but need to consider other technological circumstances.
- The production volume (moderate viability < 15 day/month > evident viability); Increasing the number of working days of production by 10% increases savings in energy costs by 12% and improves economic indicators by 20%. The impact is significant!
- The price of natural gas (moderate/weak viability < 0.46-0.50 €/m^3 > evident viability). The increase in the price by 10% increases savings in energy costs by about 9% and improves all economic indicators by 15%. The impact is significant!

Based on the presented consideration, conditions for successful heat recovery are revealed and due to the assessed good applicability, the proposed way to reduce energy consumption of the plant could be a good corporate-oriented decision.

Acknowledgement

This work is done with the close collaboration and ful support of professionals from the company Strauss Adriatic (Doncafe) from Simanovci, Serbia.

References

[1] Schwartzberg, H., *Batch Coffee Roasting; Roasting Energy Use; Reducing that Use*, Food Science Dept., Univ. of Massachusetts, Amherst, Mass., USA, 2011
[2] De Monte,, M., *et al.*, Waste Heat Recovery in a Coffee Roasting Plant, *Applied Thermal Engineering*, *23* (2003), 8, pp. 1033-1044
[3] ***, Waste Heat Recovery: Technology and Opportunities in U. S. Industry, U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy, Industrial Technologies Program (ITP), BCS, Incorporated, 2008
[4] Carolyn, J. R., An Overview of Industrial Waste Heat Recovery Technologies, Report, Washington State University, Extension Energy Program, U. S. Department of Energy, Washington, USA, 2013
[5] Changchun, X., *et al*., Performance Improvement of a 330 MWe Power Plant by Flue Gas Heat Recovery System, published online: 2014-09-06
[6] Farzaneh-Gord, M., *et al.*, Heat Recovery from a Natural Gas Powered Internal Combustion Engine by CO_2 Trans Critical Power Cycle, *Thermal Science*, *14* (2010), 4, pp. 897-911
[7] Bišćan, D., Filipan, V., Potential of Waste Heat in Croatian Industrial Sector, *Thermal Science*, *16* (2012), 3, pp. 747-758
[8] Morvay, Z., Gvozdenac, D., *Applied Industrial Energy and Environmental Management*, John Wiley & Sons, New York, USA, 2008
[9] ***. Report on Testing R14-9214, SP Laboratory AD Becej, Republic of Serbia, 2014
[10] ***, Report on Testing R14-9213, SP Laboratory AD Becej, Republic of Serbia, 2014
[11] ***, Report on the Guarantee Measurement of Pollutants Emissions from Exhaust Ventilation Channel „AEROLAB“, Belgrade, Republic of Serbia, 2014

[12] Azeredo, A. M. C. de, Coffee Roasting: Color and Aroma – Active Sulfur Compounds, Ph. D. thesis, University of Florida, Fla., USA, 2011
[13] Raemy, A., Lambelet, P., A Calorimetric Study of Self-Heating in Coffee and Chicory, *International Journal of Food Science & Technology*, *17* (1982), 4, pp. 451-460
[14] Clarke, R. J., Macrae, R., *Coffee*, *Volume 2: Technology*, Formerly of General Foods Ltd., Banbury, UK and Department of Food Science, University of Reading, UK, Elsevier Applied Science, London and New York, 1987
[15] Eggers, R., Pietsch, A., Technology I: Roasting, in: *Coffee: Recent Developments* (R. J. Clarke, O. G. Vitzthum), Blackwell Science, Oxford, UK, 2001, pp. 90-107

Paper submitted: October 13, 2015
Paper revised: November 6, 2015
Paper accepted: January 28, 2016