The Development of Heat Substation for Drying Waste Heat Utilisation

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The problem solution of waste heat utilization at the tobacco factory is considered in this work. The analysis of the possibility of waste heat utilization and appropriate calculations of plate heat exchangers were carried out. The method for multi component mixture condensation calculation is used. This allows obtaining optimal parameters for the working conditions of the heat exchangers according to the energy efficiency retrofit of industrial enterprises. The design of heat substation for waste heat utilisation was developed.

1. Introduction

Nowadays, when the cost of energy has increased dramatically, and Ukraine is its deficit, energy saving for industry is vital. Therefore, for most of Ukrainian companies it is necessary to use energy saving design methods. Industrial enterprises mostly use the energy that is obtained by fuel combustion. Part of this energy is not used and the waste heat must be derived from the chemical process system (Klemeš and Varbanov, 2012). The waste heat is heat generated in a process by way of fuel combustion or chemical reaction, which is then 'dumped' into the environment and not reused for useful and economic purposes. Depending upon the type of process, waste heat can be rejected at virtually any temperature from that of chilled cooling water to high temperature waste gases from an industrial furnace or kiln.

In considering the potential for heat recovery, it is useful to note the possibilities of the waste heat in terms of temperature potential value as shown in Table 1.

Usually higher the temperature, higher the quality and more cost effective is the heat recovery. In any study of waste heat recovery, it is absolutely necessary that there should be some use for the recovered heat. Typical examples of use would be preheating of combustion air, space heating, or pre-heating boiler feed water or process water. With high temperature heat recovery, a cascade system of waste heat recovery may be practiced to ensure that the maximum amount of heat is recovered at the highest potential. An example of this technique of waste heat recovery would be where the high temperature stage was used for air pre-heating and the low temperature stage used for process feed water heating or steam raising. Typically, in Ukraine the unused heat is removed by cold utilities which bring to the additional costs.

In recent years, more attention is paid to the use of waste heat recovery technology. An advanced energy saving system with air as the drying medium was proposed based on self-heat recuperation technology for the biomass drying.(Yuping L. et al. 2012). The technology of low potential heat utilization may be used in the hot water supply system, air pre-heating system and air heating for the fan. Boldyryev et. al.(2012) presented the possibility of ammonia low potential heat utilisation with use of Process Integration methodology. The analysis of operation of supermarket's ammonia cooling cycle has shown the

possibilities to use the overheating and condensation heat of ammonia stream. This heat can be used for air and water heating, and it will significantly reduce the utility costs.

Table 1: Waste source and quality

No.	Source	Quality
1	Heat in flue gases.	The higher the temperature, the greater the potential value for heat recovery
2	Heat in vapour streams.	As above, but when condensed, latent heat also recoverable.
3	Convective and radiant heat lost from exterior of equipment	Low grade – if collected may be used for space heating or air preheats
4	Heat losses in cooling water.	Low grade – useful gains if heat is exchanged with incoming fresh water.
5	Heat losses in providing chilled water or in the disposal of chilled water.	a) High grade if it can be utilized to reduce demand for refrigeration. b) Low grade if refrigeration unit used as a form of heat pump.
6	Heat stored in products leaving the process	Quality depends upon temperature.
7	Heat in gaseous and liquid effluents leaving process.	Poor if heavily contaminated and thus requiring alloy heat exchanger.

In our case, it was necessary to utilize the heat of condensation of steam and condensate cooling which using tobacco drying. In this study, the use of waste heat for heating and hot water storage for the needs of the tobacco plant is shown. Calculations of heat transfer equipment and economic indicators have been produced. The heat exchange unit was designed and successfully implemented into the process system.

2. Methodology

The main aspects of condensing vapour heat transfer: heat and mass transfer from flow core of condensing stream to condensate film surface, the thermal resistance of condensate film, heat transfer across the plate wall and its fouling, and also the heat transfer to cold stream flow from the plate wall. As it was shown by Tovazhnyansky et al. (2004) for multi component mixture condensation, the process can be described by one dimensional mathematical model. It enables to account for the change of process parameters along the channel length.

As it was shown by Arsenyeva et al. (2012), in channels of plate heat exchangers the heat and momentum transfer modified analogy exists. It allows calculate coefficients in correlations for heat transfer film coefficients using formula presented in cited article:

$$\text{Nu} = 0.065 \cdot \text{Re}^{6/7} \cdot \left(\psi \cdot \zeta_s / F_x \right)^{3/7} \cdot \text{Pr}^{0.4} \cdot \left(\mu / \mu_W \right)^{0.14} \tag{1}$$

Where ψ is the relative share of pressure loss due to friction in total pressure loss at main corrugated field of the channel; F_x is the surface area enlargement factor; ζ_s is friction factor on the main corrugated field of PHE channel determine by correlation presented by Arsenyeva et al. (2012); Re is Reynolds number; Pr is Prandtl number; μ and μ_w – dynamic viscosity in the main flow and at the wall, Pas.

The share of pressure losses due to friction ψ in total pressure loss:

$$A_1 = 380 / \left[\text{tg}(\beta) \right]^{1.75}; \text{ at } Re > A_1 \quad \psi = \left(\text{Re} / A_1 \right)^{-0.15 \cdot \sin(\beta)} \quad ; \text{ at } Re \leq A_1 \quad \psi = 1 \tag{2}$$

To calculate in PHE channels film heat transfer coefficient from condensate film to the plate surface, Arsenyeva et al. (2011) proposed formula based on analogy of heat and momentum transfer and homogeneous model of two phase flow:

$$Nu = Nu^* \cdot \left[1 + x \cdot \left(\frac{\rho_L}{\rho_G} \right) \right]^{0.48} \tag{3}$$

Where Nu^* – Nusselt number for condensate flow with total flow rate of two phases; x – mass vapour quality; ρ_L, ρ_G – densities of liquid and gas phases, respectively, kg/m^3.

One of the most important factors for plate condenser is pressure drop in channels. Beside its hydraulic influence it lowers the temperature of saturated vapour. In this way it reduces local temperature differences and negatively influences heat transfer. Considering increment of surface area, corresponding to the increment of channel length, we can write for condensing vapour:

$$\frac{dP}{dF} = \frac{\Delta P_{2PH} / \Delta P_G}{N_{CH} \cdot p_{CH} \cdot d_e} \zeta \cdot \frac{\rho_v \cdot W_v^2}{2} - \frac{d}{dF} \left(\frac{\rho_v \cdot W_v^2}{2} + \rho_v \cdot g \cdot F \right) \tag{4}$$

Where N_{CH} – number of channels for vapour; p_{CH} – perimeter of channel, m; W_v –velocity of vapour, m/s; g – acceleration of gravity, m/s^2; $\Delta P_{2PH}/\Delta P_G$ – the ratio of pressure drop of two phase flow to pressure drop of gaseous phase (vapour) alone.

The Lockhart-Martinelli approach is used:

$$\Delta P_{2PH} / \Delta P_G = 1 + 2.9 \cdot X_{TT}^{0.46} \tag{5}$$

$$X_{TT} = \left(\frac{G_{v0} - G_v}{G_v} \right)^{1-m/2} \cdot \left(\frac{\rho_v}{\rho_L} \right)^{1/2} \cdot \left(\frac{\mu_L}{\mu_v} \right)^{m/2} \tag{6}$$

The system of ordinary differential equations supplemented by equations characterizing the relation between variables describes the distribution of local parameters along the PHE channels. It is nonlinear and does not permit analytical solution. When the conditions on steam inlet are specified it can be solved as initial value problem by finite difference method. The channel is divided on a number Z of small zones having finite surface area ΔF. For each zone i all variables and their changes along the length of the zone are expressed through average at zone heat flux density q_i, W/m^2. The nonlinear algebraic equation is obtained, which numerical solution gives the value of q_i and after that all changes of process variables are determined. The calculations are made for all zones consequently and finally give the distribution of all process parameters along the PHE channel. The algorithm is implemented as software for PC.

To validate the accuracy of developed mathematical model and software the calculations were made for steam condensing in the channel of constant form of corrugations and cross section area. The number of division zones was 16. The comparison with presented experimental data have shown: error for calculation of film heat transfer coefficients not exceeded 5 %; for total pressure drop of steam error not more than 11 %.

3. Data extraction

Data on existing tobacco drying process were analyzed. Tobacco is fed into a drying tower with 22.5 % moisture content. Drying is carried out in a stream of superheated steam at a temperature of 180 ^{0}C. In the cyclone tobacco is deposited and the returns are further moisture. Tobacco is discharged from the cyclone with lock assembly. After that tobacco leaves drying tower with 14.5 % moisture content. The air-steam mixture is returned to the drying circuit through the heat exchanger to maintain the desired temperature. Part of steam injection, and the secondary steam are removed into the atmosphere through the control valve. Steam flow through the valve varies from 950 – 1,100 kg/h at temperature 140 ^{0}C. In operation, the damper is open to 15-19 %. PHE module recovers the heat of the secondary vapor (see Figure 1). The steam is condensed in a plate condenser and transfers heat to the heating plant.
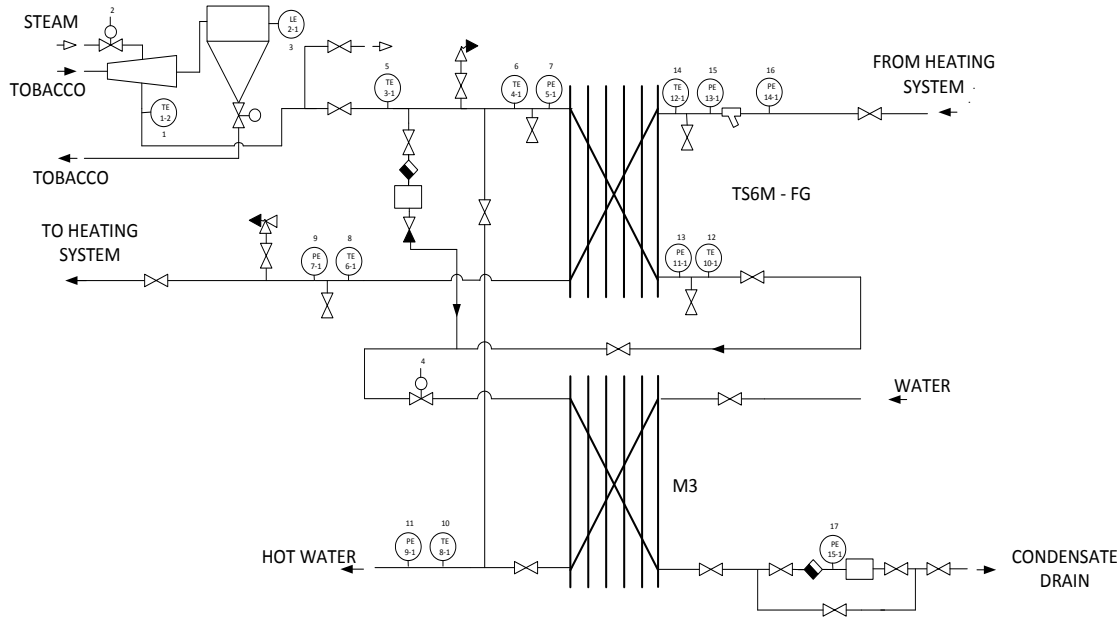
Figure 1: Process flow diagram of automated module utilization of waste heat stream

The condensate flows in a PHE - heater and heat the water for the needs of the factory. Streams which have been identified can use waste heat exhaust steam. The technological streams information is provided in Table 2.

Table 2: Stream data of the existing process

No	Stream	Type	T_S, °C	T_T, °C	G, kg/s	CP, kW/K	ΔH, kW
1	Steam	Hot	110	88	0.278	25.7	566
2	Condensate	Hot	88	30	0.278	1.2	67
3	Ethylene glycol	Cold	50	70	7.640	28.8	566
4	Hot water	Cold	5	55	0.320	1.34	67

Exhaust steam condensation heat can be utilized for heating water glycol mixing, which is circulated in the heating system. The remaining heat can be used for heating hot water (Figure 2).

4. Design and implementation

Automated heat recovery heat exchanger module was designed, and it is shown in Figure 1. The steam is condensed in a plate condenser and transfers heat to the heating plant. The condensate flows in a plate heat exchanger and heat the water for the needs of the factory. PHEs are one of the efficient types of heat exchangers with intensified heat transfer caused by enhanced turbulent parameters in channels (Arsenyeva et al., 2013). As the steam condenser TS6M-FG plate heat exchanger (Alfa Laval, 2003) was selected. The TS Series plate heat exchanger is designed exclusively for steam-to-water heating for the most versatile water applications, including hot water sets for pasteurizers, pre-heating water for injection applications(WFI), and cleaning in place (CIP) solution heating. Equipped with a unique plate geometry that eliminates thermal fatigue, each PHE is built with large inlets and high temperature gaskets-along with a strong, heavy duty frame-proving time after time that it can take the heat and pressures associated with steam and water applications. As an ideal replacement for shell-and-tube heat exchangers, the TS Series is typically used for closed-loop hot water systems found in pasteurizers and heating clean-in-place solutions.
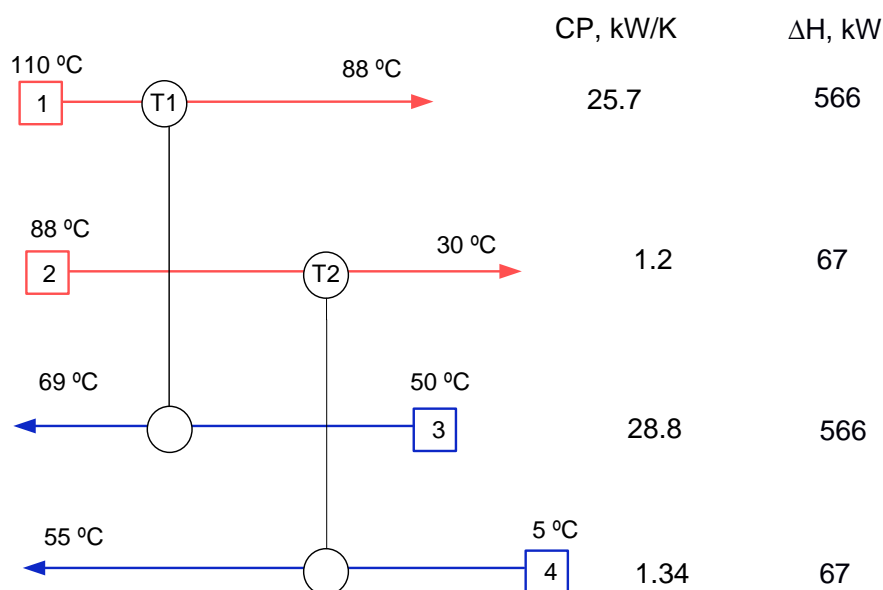
	CP, kW/K	ΔH, kW
110 ºC → T1 → 88 ºC	25.7	566
88 ºC → T2 → 30 ºC	1.2	67
69 ºC ← ... ← 3 (50 ºC)	28.8	566
55 ºC ← ... ← 4 (5 ºC)	1.34	67

Figure 2: Grid diagram of recuperative heat exchanger network

Table 3: The results of calculating PHEs

	Heat load, kW	OHTC[1], W/(m²K)	Heat transfer area, m²	Fouling resistance * 10,000 m²·K/W	Number of plates
TS6M-FG	545	2,573	4.1	0.012	50
M3	67	6,506	0.4	0.015	13

[1]overall heat transfer coefficient

While the TS Series plate heat exchanger has excellent temperature control characteristics, shell-and-tube heat exchangers have a slow response to load changes and a large hold-up volume. Straight shell-and tube heat exchangers are also prone to thermal fatigue due to the rigid, cyclic heating and cooling produced. This type of thermal fatigue often results in cracked or worn components that demand maintenance and repair, causing unwanted system downtime. The combination of thin but durable TS plates and flexible gaskets in the TS Series prevents thermal fatigue by allowing the unit to slightly expand or contract in response to temperature changes. Unlike shell-and-tube heat exchangers, the minimal volume between the TS plates enables them to continue to function normally during stalling - that is, under vacuum - which leads to a build-up of condensate in the heat exchanger.

Table 4: The results of heat substation implementation

Item	Value
Design cost, €	6,056
Total equipment cost, €	40,495
Total capital cost, €	46,551
Annual operating cost, €/y	11,482
Annual economy, €/y	121,725
Annual income, €/y	89,297
Payback period, y	0.52
The coefficient of investments efficiency, €/€	1.92

This phenomenon occurs when heating water to less than 100 °C. In shell-and-tube heat exchangers, this leads to big problems with temperature control, as well as steam implosions that can damage the heat exchanger and associated equipment through water hammer. As a compact plate heat exchanger, the TS Series weighs less, requires fewer floors, space, and is easier to install, service, and modify - especially for hot water skids where space is a premium. In place of shell-and-tubes, a TS heat exchanger can easily

reduce the overall hot water package footprint by 50 %. The compact design allows for easier configuration and assembly - saving valuable installation time and costs. List of PHE key parameters is shown in Table 3.

5. Results – economic efficiency

The results of implementation of low grade steam energy potential to heat water for radiator heating and tap water heating with use of specially designed heat substation are presented in Table 4.

6. Conclusions

The problem of waste heat utilization at the tobacco factory was solved with use of high effective plate heat exchangers. Low-grade steam energy potential to heat water for radiator heating and tap water heating was realized in designed special heat substation. As the basic equipment for heat substation the special plate heat exchangers TS6M-FG and M3 were selected. Annual economy reaches more than 120 k€.

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