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Utilization of Process Wastewater Heat

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1. Introduction

The requirements of sustainable development of the economy cause that in the energy policy of industrial plants more and more attention is paid to the possibility of heat recovery from various types of process waste, including industrial wastewater. This is mainly due to increasing costs of energy for production purposes, as well as for heating and ventilation of production halls. In the case of wastewater at elevated temperature, heat utilization makes it possible to achieve greater economic effect. For comparison, the temperature of municipal wastewater is within the range of 10-20ºC, whereas in the case of industrial wastewater it can be above 40ºC. It is worth noting that lowering the temperature by 1ºC makes it possible to obtain 1.16 kW of heat from 1 m^3/h of wastewater (Górski & Matuszewska 2013, Kosieradzki 2009, Noch et al. 2018). In some branches of industry it is possible to recover heat even up to 60% of the plant's heat balance (Wodołażski 2015).

In the case of industrial wastewater disposal to a biological treatment plant, heat recovery becomes a key and necessary element. The decrease of wastewater temperature accompanying recovery allows for more effective removal of colloidal and suspended matter from it, and thus - for further decrease of treatment costs at the treatment plant. In addition, industrial wastewater at elevated temperature can constitute a significant threat to the natural environment from an ecological point of view. Therefore, utilization of wastewater heat in industrial plants is not only economically but also ecologically justified, as it reduces its potentially negative impact on the environment.

In those places where wastewater is generated continuously and in large quantities, heat utilization is economically justified. On the market there are ready-made devices for heat utilization. The most commonly used are heat exchangers and heat pumps, which are used to recover heat from wastewater from various technological processes (Górski & Matuszewska 2013). However, it should be emphasized that wastewater as an energy source is a resource with limited thermal potential and variable characteristics. It depends on the process in which it came from and on the amount of water consumed. The variable physicochemical composition of wastewater and its unspecified quantity very often makes it difficult to use ready-made technical solutions available on the market.

2. Object, target and research methodology

The Homanit company was selected to be the object of research and the said company is located in the town of Karlino in the West Pomeranian Province of Poland. The plant produces thin, highly refined medium and high density fiberboards (MDF and HDF). Among many production cycles, a steam thermal treatment of wood cycle was selected, which produces around 8.3 m^3/h of wastewater per day at an average temperature of 80ºC. This wastewater contains a number of chemical pollutants. The main ones are sugars that occur in the form of disaccharides. These carbohydrates include mannose, arabinose, galactose, xylose and glucose, cellulose and hemicellulose. Organic acids, such as formic and acetic, are also present, and in trace amounts – propionic acid. In addition, there are contaminants from mechanical wood processing: sand and a fine fraction of wood fiber with average dimension of approx. 1 mm. The wastewater shows acidic reaction within the range of pH = 5.0-5.5.

Wastewater, due to its composition, tends to coagulate and stick to the pipeline walls. For this reason, as well as to reduce the costs associated with wastewater treatment in a station located in Kołobrzeg, the wastewater is pretreated at the plant. For this purpose, a centrifuge is used; its efficiency is greatly reduced due to high temperature of wastewater. The centrifugation technology is based on the assumption that temperature of the centrifuged medium should not exceed 40ºC. To lower the temperature, two mechanical draft cooling facilities are currently used. Their efficiency is not always sufficient to cool the peak wastewater stream to the required temperature. Furthermore, wastewater heat is not utilized.

The purpose of this research work was to develop a concept for reliable cooling of variable-flow wastewater with heat recovery for heating or production purposes. The research methodology consisted mainly of theoretical computation based on the initially obtained technological information and partly on the measurements made.

3. Computation results

3.1. Shell-and-tube heat exchanger for heating purposes

Water heating for the purposes of heating the production building was considered as the first variant of wastewater heat utilization. The concept of a shell-and-tube heat exchanger was developed, which consists of a cylindrical shell and a bundle of straight, thin-walled tubes. The heat exchange surface is the surface of the tubes along which the heat exchange takes place between cooling water flowing inside these tubes and wastewater flowing around them. The decision to use such an exchanger design, which is nowadays considered obsolete, is based on facilitating the cleaning of the area around the tubes to which wastewater is channeled.

Structural computation of the shell-and-tube heat exchanger were made based on the following initial assumptions for the medium streams:

- hourly wastewater flow: $V_1 = 8.3$ m^3/h,
- initial wastewater temperature: $t_1' = 90$ºC,
- expected wastewater temperature after cooling: $t_1'' = 40$ºC,
- initial temperature of cooling water: $t_2' = 20$ºC,
- expected temperature after cooling: $t_2''= 80$ºC.

The physical properties of the wastewater were adopted as for water at an average temperature of $t_1^{av.} = 65$ºC: specific heat $c_p = 4183$ kJ/(kg·K); density $\rho = 980.5$ kg/m^3. The above data shows that the recovered heat flux is:

$$Q_1 = \frac{V_1}{3600}\rho c_p\left(t_1' - t_1''\right) = \frac{8.3}{3600}980.5\cdot 4.183\left(90-40\right) = 472.8 \text{ kW}.$$

From the enthalpy balance under the above assumptions, mass flow rates of the mediums were determined: for wastewater $M_1 = 2.26$ kg/s; for water $M_2 = 1.89$ kg/s.

The exchanger shell is expected to be made of steel seamed pipe 114×2.5 mm with an internal diameter of 109 mm, while the tube bundle will consist of seamless steel tubes 12×1 mm with internal diameter of 10 mm. The recommended flow rate of mediums for such exchanger design was adopted (Piotrowski 1973): for the inter-tube area (cooled wastewater) - 0.45 m/s; for a tube bundle area (cooling water to be used as a heating medium) - 0.65 m/s.

Fig. 1 shows the exchanger cross-section obtained as a result of the design on the condition that the inter-tube area is optimally filled. The number of tubes in the bundle was 37. For such a design, the actual flow rates of mediums were: for inter-tube space $w_1 = 0.45$ m/s; for tube bundle area $w_2 = 0.66$ m/s.

The following physical properties of mediums were applied in further thermal computation (Szkarowski et al. 2017):

- For wastewater at average temperature $t_1^{av.}$ = 65°C:
  - Prandtl number: $Pr_1 = 2.765$,
  - specific heat: $c_{p1} = 4.183$ kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_1 = 0.447 \cdot 10^{-6}$ m^2/s,
  - thermal conductivity coefficient: $\lambda_1 = 66.35 \cdot 10^{-2}$ W/(m·K),
  - density $\rho_1 = 980.5$ kg/m^3,
- for cooling water at average temperature $t_2^{av.}$ = 50°C:
  - Prandtl number: $Pr_2 = 3.54$,
  - specific heat: $c_{p2} = 4.174$ kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_2 = 0.556 \cdot 10^{-6}$ m^2/s,
  - thermal conductivity coefficient: $\lambda_2 = 64.8 \cdot 10^{-2}$ W/(m·K),
  - density $\rho_2 = 988.1$ kg/m^3.

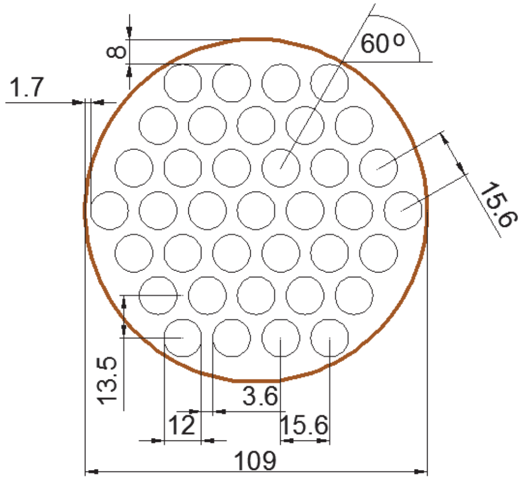


Fig. 1. Cross-section of the wastewater-water heat exchanger

Based on the above values of physical properties and velocity of mediums, the value of Reynolds number was determined for the adopted exchanger design:

- for wastewater in inter-tube area: $Re_1 = 12100$,
- for water in pipes: $Re_2 = 11870$,

which proves the developed turbulent movement of both mediums. This gives an opportunity to determine the Nusselt number, which characterizes heat transfer on the surface of the tube bundle, from the universal formula (Szkarowski et al. 2017): for wastewater on the outer surface of tubes $Nu_1 = 61.23$; for water on the internal surface of tubes $Nu_2 = 67.06$.

The above premises were used to determine the value of the heat transfer coefficient, which for the wastewater side is $\alpha_1 = 3385$ W/(m^2·K), and on the water side $\alpha_2 = 4295$ W/(m^2·K). The value of the heat transfer coefficient, taking into account the material and wall thickness of the tubes, is 1681 W/(m^2·K).

The nature of the variation of temperature of the mediums along the heat exchange surface allows the active temperature difference to be taken as the arithmetic mean (Orłowska 2018), which amounts to $\Delta t = 15°C$. The required surface of the tube bundle with the above heat exchange characteristics was about 18.52 m^2, and the length of the tubes in the bundle was 13.28 m. In order to shorten the heat exchanger length, the series connection of three sections of 4.5 m long each was suggested.

Hydraulic computation were also performed to determine fluid pressure loss during flow through the exchanger. The required power to drive the wastewater pump was approximately 260 W, while the power required for the water pump – approximately 540 W.

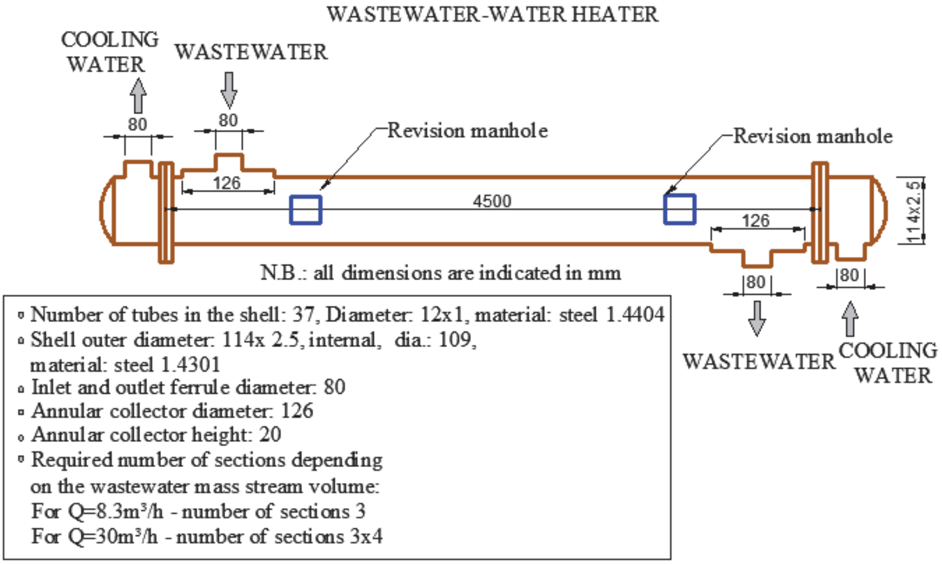
Dimensions and basic characteristics of the designed heat exchanger are shown in Fig. 2. Inspection hatches are provided for cleaning the space between the tubes. An annular collector is provided at each wastewater inlet and outlet. Its dimensions were chosen so that the medium velocity in the connector, in the annular channel and in the inter-tube area be similar.

It should be emphasized that several Polish companies manufacturing heat exchangers would propose ready-made solutions for the obtained preliminary results. However, a certain problem would be the need to periodically quickly clean the inter-tube area.

3.2. Ventilation heater

An air heater was developed as a second way to cool the wastewater and recover its heat. Currently, an oil heater is used to heat the outside air for ventilation of the factory boiler room. Most of this air is used to burn fuel in boilers.

A two-row tube type "wastewater-air" exchanger with cross flow of mediums and cross-section of 5×5 m was chosen. The vertical ribbed tubes constitute the heat exchange surface. Heat exchange takes place between wastewater flowing inside these tubes and air flowing across them - horizontally. Due to the large stream of heated air and expected expansion of the plant, a decision was made to calculate the maximum daily wastewater flow.



- Number of tubes in the shell: 37, Diameter: 12x1, material: steel 1.4404
- Shell outer diameter: 114x 2.5, internal, dia.: 109, material: steel 1.4301
- Inlet and outlet ferrule diameter: 80
- Annular collector diameter: 126
- Annular collector height: 20
- Required number of sections depending on the wastewater mass stream volume:
  For Q=8.3m³/h - number of sections 3
  For Q=30m³/h - number of sections 3x4

Fig. 2. Basic characteristics of one section of the wastewater-water heat exchanger

Design-verification computation of the cross-flow exchanger was made based on the following initial assumptions for the mediums streams:

- initial wastewater temperature: $t_1' = 90$ºC,
- expected waster water temperature after cooling: $t_1'' = 40$ºC,
- hourly wastewater flow: $V_1 = 30$ m^3/h,
- hourly air flow: $V_2 = 485{,}000$ m^3/h,
- initial external air temperature $t_2' = -10$ºC.

Physical properties of wastewater were assumed initially as for water at arithmetic average temperature $t_1^{av.} = 65$ºC C: specific heat $c_p = 4183$ kJ/(kg·K); ρ = 980.5 kg/m^3. The above data shows that the recovered heat flux is:

$$Q_1 = \frac{V_1}{3600}\rho c_p\left(t_1' - t_1''\right) = \frac{8.3}{3600}980.5\cdot 4.183\left(90-40\right) = 1702\ \text{kW}.$$

This allowed for the determination of the final air temperature: $t_2'' = 0$ºC. The nature of mediums temperature variation along the heat exchange surface requires the use of active temperature difference as the logarithmic mean

(Orłowska 2018), which was $\Delta \boldsymbol{t} = 68.12\,^{\circ}\mathrm{C}$. In this conditions the average wastewater temperature is:

$$\boldsymbol{t}_1^{av.} = \boldsymbol{t}_2^{av.} + \Delta \boldsymbol{t} = \frac{-10+0}{2} + 68.12 = 63.12\,^{\circ}\mathrm{C}.$$

For this temperature we have the following properties of wastewater: $\boldsymbol{c}_p$ = 4181 kJ/(kg·K); density $\rho = 981.5$ kg/m^3, which needs slight correction of the recovered heat flux:

$$\boldsymbol{Q}_1 = \frac{8.3}{3600} 981.5 \cdot 4.181 (90 - 40) = 1703\,\mathrm{kW}.$$

From the enthalpy balance under the above assumptions, mass flow rates of mediums were determined: for wastewater $\boldsymbol{M}_1 = 4.52$ kg/s; for air $\boldsymbol{M}_2 = 33.8$ kg/s.

The design of the double-row "wastewater-air" heater obtained as a result of computation is shown in Fig. 3. For the selected diameter of vertical tubes 33.7×2.0 mm, dimensions of the square ribs are 7.4×7.4 cm. Thickness of the metal plate is 1 mm, and the distance between the rib axes is 3 mm.

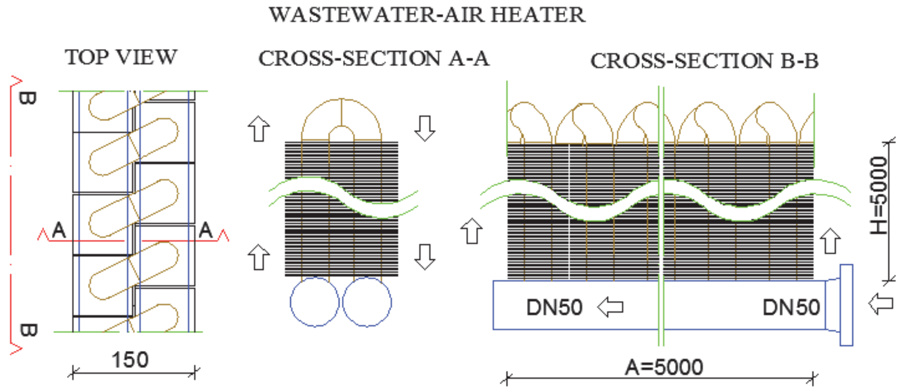
The assumed wastewater velocity in the tubes was 0.45 m/s, while real air velocity in the inter-tube area was 14.2 m/s.

The following physical properties of mediums were adopted for further thermal computation (Szkarowski et al. 2017):

- For wastewater at average temperature $\boldsymbol{t}_1^{av.} = 63.12^{\circ}\mathrm{C}$:
  - Prandtl number: $\mathrm{Pr}_1 = 2.846$,
  - specific heat: $c_{p1} = 4.181$ kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_1 = 0.458 \cdot 10^{-6}$ m^2/s,
  - thermal conductivity coefficient: $\lambda_1 = 66.18 \cdot 10^{-2}$ W/(m·K),
  - density $\rho_1 = 981.5$ kg/m^3,
- for cooling air at average temperature $\boldsymbol{t}_2^{av.} = -5\,^{\circ}\mathrm{C}$:
  - Prandtl number: $\mathrm{Pr}_2 = 0.71$,
  - specific heat: $c_{p2} = 1.007$ kJ/(kg·K),
  - kinematic viscosity coefficient: $\nu_2 = 12.855 \cdot 10^{-6}$ m^2/s,
  - thermal conductivity coefficient: $\lambda_2 = 2.4 \cdot 10^{-2}$ W/(m·K),
  - density $\rho_2 = 1.318$ kg/m^3.

Based on the above values of physical properties and velocity of mediums, the value of Reynolds number was determined for the adopted exchanger design:

- for wastewater in tubes in the inter-tube area: $Re_1 = 32424$,
- for air in the inter-tube area: $Re_2 = 170000$.



CHARACTERISTIC:
- Heater width: 5m
- Heater height: 5m
- Number of tubes in one row: 66
- Number of tubes in the second row: 65
- Vertical tubes diameter: DN25: DN25 (33.7x2mm)
- Collector diameter: DN50 (60.3x2.9mm)

Fig. 3. Cross-section of the designed "wastewater-air" heater

The above allowed for the opportunity to determine the Nusselt number from appropriate formulas (Szkarowski et al. 2017): for wastewater on the inner surface of tubes: $Nu_1 = 189.22$; for air on the outer surface of ribbed tubes: $Nu_2 = 368.2$.

From the above premises, the value of the heat transfer coefficient was determined, which on the wastewater side is $\alpha_1 = 4216.4$ W/(m^2·K) and on the water side $\alpha_2 = 50.3$ W/(m^2·K). The value of the heat transfer coefficient, taking into account the material and wall thickness of the tubes, is 15.64 W/(m^2·K).

The required ribbed surface at this heat exchange intensity is about 1374 m^2, with an area of one row equal to 1023 m^2. Such design of the exchanger in the assumed computation conditions will provide air temperature behind the heater of about 0°C, which will reduce the strain on heaters generating heat for the boiler by up to 50%. As the outside temperature increases, the designed exchanger will be able to provide more heat and even cover 100% of the demand for ventilation purposes.

4. Summary

The possibility of process wastewater heat recovery was estimated at Homanit plant located in Karlino, Poland. To determine the volume of heat recovered, a steam thermal treatment of wood cycle was selected, which currently generates about 8.3 m^3/h of wastewater at average temperature of 80°C. The need to cool down wastewater in order to improve the efficiency of wastewater pretreatment by centrifugation provided an additional motive.

A shell-and-tube heat exchanger was developed, the purpose of which is both cooling wastewater to the desired temperature and heating water, which will then serve as a heating medium for heating a production building. The heat exchange surface consisting of straight, thin-walled tubes is approximately 18 m^2. The recovered heat flux with an average daily wastewater flow is 473 kW.

A cross-flow heater was developed, the purpose of which is to cool wastewater and heat outside air for ventilation of the boiler room. The heat exchange surface of vertical ribbed tubes is approx. 1532 m^2. The theoretical thermal power recovered from the wastewater stream with a maximum daily flow is 1703 kW.

References

Górski, J., Matuszewska, D. (2013). Możliwości pozyskiwania ciepła odpadowego ze ścieków i systemów kanalizacji. *Piece Przemysłowe & Kotły, 7-8*, 21-28.

Kosieradzki, J. (2009). Odzysk ciepła – możliwości i zasady. *Rynek instalacyjny*, *3*, 55-58.

Noch, T. et al. (2018). Analiza emisji zanieczyszczeń w wyniku wytwarzania energii cieplnej. *Rocznik ochrona środowiska, 20,* 1181-1198.

Orłowska, M. (2018). Badanie wpływu właściwości termicznych okna na pracę grzejnika w pomieszczeniu – badania numeryczne. *Rocznik Ochrona Środowiska, 20*, 1699-1709.

Piotrowski, Z. (1973). *Aparatura ogrzewcza w ciepłownictwie*. Warszawa: Wydawnictwa Politechniki Warszawskiej.

Szkarowski, A., Pavlenko, A., Koshlak, A. (2017). *Zagadnienia wymiany ciepła i masy w inżynierii środowiska*. Koszalin: Wydawnictwo Politechniki Koszalińskiej.

Wodołażski, A. (2015). Znaczenie odzysku ciepła odpadowego z instalacji produkującej dimetyloeter w ochronie środowiska. *Rocznik Ochrona Środowiska, 17,* 1674-1683.

Abstract

This papers presents the results of computation of two heat exchangers used for heat utilization of industrial wastewater generated in a refined fiberboard production plant. The basic task was to cool wastewater to a temperature of approximately 40°C enabling efficient centrifugation of suspended matter at the stage of wastewater pretreatment. A shell-and-tube heat exchanger with the power of 473 kW for water heating was developed for heating the production hall. A cross-flow exchanger was also developed for heating ventilation air in the boiler room building, power of which is 1703 kW.

Thermal and hydraulic computation was performed, the required heat exchange surface was selected, the main structural characteristics of both exchangers were determined.

Keywords:
process wastewater, heat recovery, shell-and-tube heat exchanger,
cross-flow heat exchanger

Utylizacja ciepła ścieków poprodukcyjnych

Streszczenie

W niniejszym artykule przedstawiono wyniki obliczeń dwóch wymienników ciepła typu służących do utylizacji ciepła ścieków przemysłowych powstających w zakładzie do produkcji uszlachetnionych płyt pilśniowych. Zadaniem podstawowym było schładzanie ścieków do temperatury ok. 40ºC umożliwiającej sprawne odwirowanie zawieszonych substancji na etapie wstępnego podczyszczania ścieków. Opracowano wymiennik płaszczowo-rurowy podgrzewający wodę na cele ogrzewania hali produkcyjnej o mocy 473 kW. Opracowano również wymiennik krzyżowy na cele podgrzania powietrza wentylacyjnego w budynku kotłowni, którego moc wynosi 1703 kW. Wykonano obliczenia cieplne i hydrauliczne, dobrano wymaganą powierzchnię wymiany ciepła, określono główne charakterystyki konstrukcyjne obu wymienników.

Słowa kluczowe:
ścieki produkcyjne, odzysk ciepła, wymiennik płaszczowo-rurowy,
wymiennik krzyżowy