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Identification of the Most Effective Heat Exchanger for Waste Heat Recovery

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Laboratory of Energy Intensive Processes placed in the building of NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology, is a research laboratory focused on increasing efficiency of industrial plants. Current research in the laboratory focuses on improving of the energy efficiency of industrial laundries. That can be achieved for example by recovery of the heat produced in the process. A microturbine is used as a power source. It produces flue gas with temperature approximately 300 °C. This flue gas is currently leaving into ambient air without utilization of its heat. Temperature this high enables utilization of the waste heat for preheating the combustion air or for heating water for various purposes.
In this article, an evaluation procedure of several types (both conventional and special) of heat exchangers that are suitable for utilization of flue gas' waste heat and the possibilities of their intensification will be described. It will be shown that heat exchangers with enhanced surfaces are more suitable for the application than exchangers with plain tubes. For heat exchange intensification it is possible to use various types of finned tubes or inserts. This enhancement increases turbulence and thereby heat exchange but also pressure loss. It is therefore, necessary to find suitable solution that will meet the condition of maximal allowed pressure loss while size of the device will be acceptable at the same time.
Different types of heat exchangers with various possibilities of intensification and their influence on the heat transfer and pressure loss will be described in the article. The overall suitability of each type of heat exchanger for the current application will be briefly discussed. Selected types of exchangers will be made and tested in the above mentioned laboratory.

1. Introduction

This article deals with the identification of the most suitable type of heat exchanger for use of waste heat from a microturbine, which is part of laundry process. This unit is located in the Laboratory of Energy Intensive Processes placed in the building of NETME Centre, Faculty of Mechanical Engineering, Brno University of Technology and is used at a research focused on increasing efficiency of industrial plants.
In order to achieve high process efficiency that would in turn lead to reduction of operational costs, as much heat energy as possible must be reasonably used. This is termed as the waste heat recovery. The suitable way to reach this goal seems to be the use of waste heat to heating the other process media via a heat exchanger.
Waste heat is contained in the flue-gas produced by gas microturbine. The reduction of the energy intensity of the washing process can be achieved by heating of the drying air or the water, subsequently used in the laundry process. Both variants ensure lowering of operational costs and improving the efficiency of the laundering process.
Selection of a suitable heat exchanger type is of primary importance in design of these systems. It is necessary to perform the design of heat exchanger in relation to process parameters like temperature, composition of process fluids, fouling propensity and potential operational problems (Kilkovsky et al., 2014).
Heat exchangers can be classified according to various aspects. For example according to their flow arrangement are parallel-flow, counter-flow and cross-flow. According to contact mechanism between hot

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and cold fluids are divided into recuperative, regenerative and direct contact heat exchangers. Also, heat exchangers can be classified on the basis of their geometric such as double pipe, shell and tube, spiral tube, gasket, spiral plate, lamella, finned plate and finally finned tube heat exchangers (Kuppan, 2000).
Designers mostly prefer using conventional types of heat exchangers (like e.g. shell-and-tube, plate or plate-fin ones), however, in some cases it is necessary to use tailor-made heat exchangers from various reasons given by specific features of processes. Nowadays, researchers have tried to improve heat transfer efficiency through special design of conventional heat exchangers. Some efficient techniques are available to increase heat transfer rates in heat exchangers and can be classified into two main groups, active and non-active methods (Stehlík et al., 2014).
According to (Kolev and Kolev, 2002), different types of installations can be used to utilize waste heat, for example: contact economizer systems of first, second and third generations, and, heat exchangers with aluminum fins, apparatuses of the "KTAN" type and Compabloc plate heat exchanger produced by Alfa Laval.
Apart from conventional heat exchangers, also special heat exchanger types designed specifically for particular applications are often used – these are the so called tailor made heat exchangers. Very interesting examples of tailor made heat exchangers used in microturbines are a multi-coil helical pipe heat exchanger (Wang et al., 2013) (Figure 1) or a tubular heat exchanger (Kocich et al., 2012) (see Figure 2). Nevertheless, a conventional exchanger will be used in the current application due to its lower capital cost.

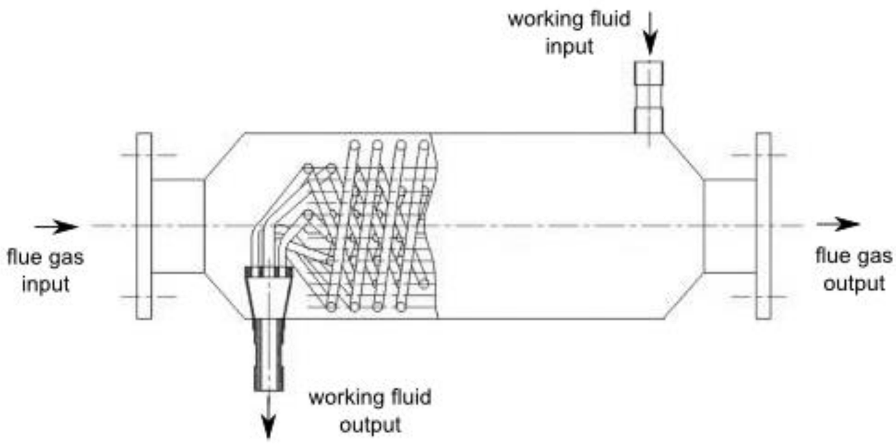

Figure 1: Multi-coil helical pipe heat exchanger (Wang et al., 2013)

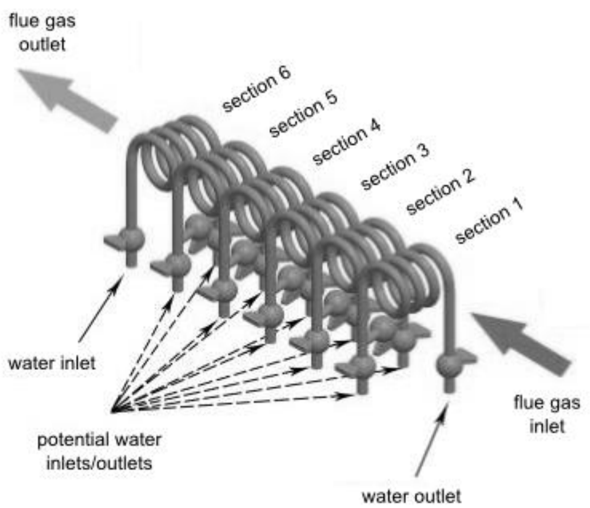

Figure 2: Tubular heat exchanger (Kocich et al., 2012)

2. Process parameters

Microturbine operating at the given unit has its own heat exchanger designed to preheat combustion air from the resulting flue-gas. Flue-gas has still high temperature and leaving into the environment without any utilization. Flue-gas heat should be recovered to another process medium (air or water) and thus reduce the energy intensity of the process. The heated air would be used as drying air while the heated water would be used in the laundry process. The parameters of process streams are given in Table 1. Selected exchanger will be placed directly after the gas turbine.
As follows from the balance (see Figure 3), in the case of "flue-gas – air" the required heat exchanger duty is 56,258 W and flue-gas output temperature is 114.2 °C. In the case of "flue-gas – water" the required heat exchanger duty is 74,754 W and flue-gas output temperature is 33.4 °C (which is still at the combustion conditions in the microturbine above the dew point).

Table 1: Parameters of process streams

	Flue-gas*	Air**	Water***
Flow rate, kg/s	0.28	0.2436	0.2
Flow rate, m^3/h	1,705.6 (at 305 °C)	885 (at 70 °C)	0.730
Input temperature, °C	305	22	15
Output temperature, °C	-	250	110
Allowed pressure drop, kPa	1.5	2.2	50

**Compositon of flue-gas (vol.%): N_2 75.962, O_2 17.514, Ar 0.914, CO_2 1.477, H_2O 4.133*
***Relative humidity 40 % ±15 %*
****Pressure of water 6 - 7 bar*

3. Analyzed heat exchangers and results

For our case of waste heat recovery were mentioned conventional heat exchangers with plain and enhanced surfaces because of low investment cost. This means tubular heat exchangers, plate heat exchangers and compact heat exchangers (see Figure 4).

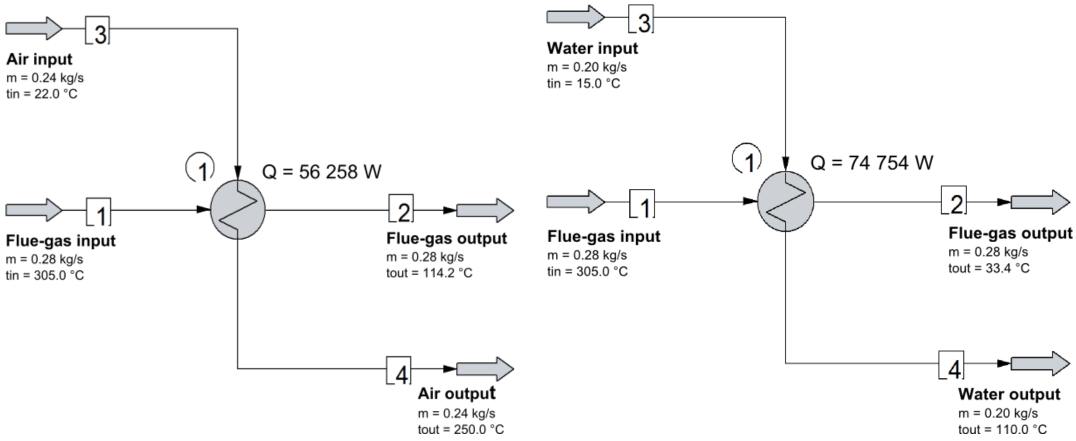

Figure 3: Heat balance of solved heat exchanger (label "1") - cases a) Flue-gas – Air b) Flue-gas – Water"

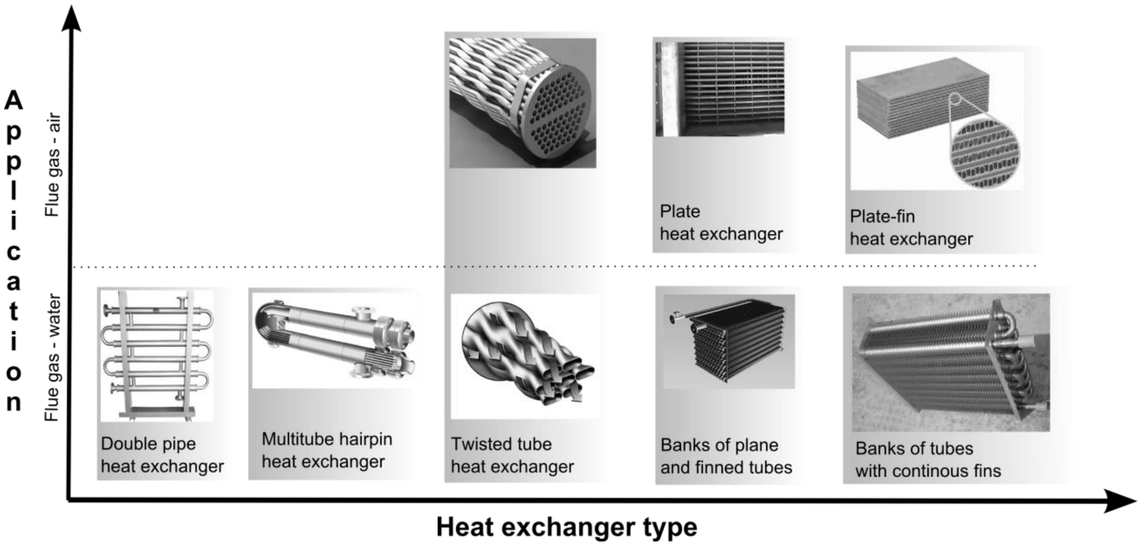

Figure 4: Analysed conventional types of heat exchangers

Tubular heat exchangers with plain tubes are still widely used. For their design are sufficiently validated calculation formulas and production is relatively simple and inexpensive. Moreover, if the flue gas temperature is significantly lower than 500 °C, then enhanced heat transfer surfaces are beneficial (Kilkovsky et al., 2014). These exchangers can be classified as compact heat exchangers. At present compact heat exchangers are more and more preferred. In general, compact heat exchangers have a larger heat transfer area related to unit volume than conventional types. Some of the advantages of compact heat exchangers include higher effectiveness, smaller volume, multi-stream & multi-pass configurations, tighter temperature control, power savings, improved safety, and radical approach to plant design. According to (Hesselgreaves, 2001), compact heat exchangers can be classified into three main categories:

- Tube-fin heat exchangers;
- Plate type and plate-fin heat exchangers and their derivatives;
- Compact heat exchangers with precision formed surfaces.

Following this classification, the suitability of selected types of exchangers, i.e. heat exchangers with plain heat transfer area and compact heat exchangers, was evaluated.

3.1 Double pipe heat exchanger

When using plain tubes and gaseous medium, the exchanger would have to be very long (about 170 m) in order to reach the desired heat duty. This obviously has a negative impact on pressure drop. This type is therefore inappropriate for the present application.

By using finned tubes we significantly reduce tube length. The required heat exchanger size is then as much as three times smaller for the finned tube heat exchanger compared to the exchanger with plain tube. However, the pressure drop is still not under the allowed value. This is still insufficient and the heat exchanger is simply too large for the given application. While the simplest type available, it is suitable to accommodate only small heat duties.

A way to further improve efficiency of double pipe heat exchangers with finned tube is with special types of fins (Stehlík et al., 2014) (see Figure 5). With these the length of the heat exchanger could already be acceptable.

3.2 Multitube hairpin heat exchanger

When using a bundle of plain tubes without baffle system located in the shell, length of the heat exchanger is, similarly to the double pipe heat exchanger, too large. This geometry is therefore unusable as well.

Increasing the efficiency of the heat exchanger can be achieved by using longitudinally finned tubes. These fins provide extended heat transfer area with relatively low resulting pressure drops. By using this solution, the length of the heat exchanger is already significantly smaller and almost within acceptable limits. Another possibility to increase the efficiency of heat exchange is by using a special type of finned tubes (Figure 6).

In all previous cases, the flue-gas has been considered in the calculations as passing through the shell side of the exchanger. In case of using inserts, it is possible to place the flue-gas into the tubes and water into the shell sides. When using a higher amount of tubes with inserts in the shell, the allowed pressure drop can be met. Just as inserts, we can use various types of turbulators. This type of heat exchanger thus represents one possible solution for the given application.

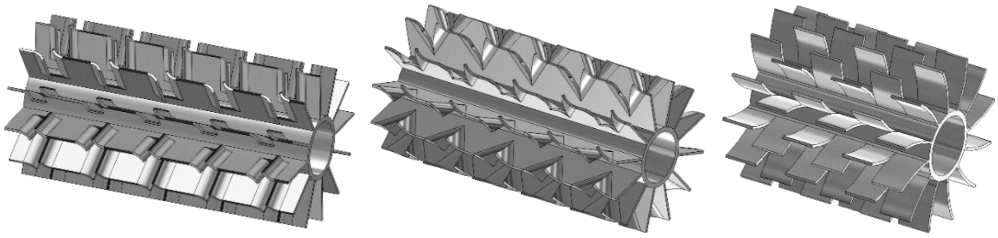

Figure 5: Newly developed longitudinally finned tubes (Stehlík et al., 2014)

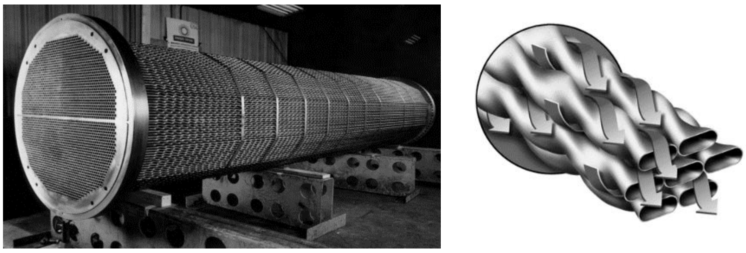

Figure 6: Twisted tube heat exchanger (Morgan, 2015)

3.3 Twisted tube heat exchanger

Twisted tube exchangers consist of a bundle of uniquely formed tubes assembled in a bundle without the use of baffles (Figure 6). The tubes have been subjected to a unique forming process which results in an oval cross section with a superimposed helix providing a helical tube-side flow path (Morgan, 2015). The heat transfer coefficient and pressure drop depend on size of flattening.

Application Flue-gas – Water

With this type of heat exchanger and placing water into the tubes can be achieved at a small diameter of shell tube length below one meter. This type of heat exchanger and arrangement can be used for the given application.

Application Flue-gas – Air

Here the situation is much more complicated. Using simplified calculation it was found that it is possible to get an acceptable solution for the case when air was placed into tube side and flue-gas into shell side. This type of heat exchanger and arrangement can therefore also be used for the given application.

3.4 Banks of plain and finned tubes

This heat exchanger represents a bank of tubes in which the process media flow at the so-called crossflow arrangement. When plain tubes are used and water flows in the tubes and flue gas on the shell side the heat transfer area of the heat exchanger is too high. This geometry is therefore not suitable for the given application.

To improve the situation we can use enhanced heat transfer surface. For tubes it is possible to use different types of fins (e.g. low fins, high fins, serrated fins, spirally wound fins) or studs. When using tubes with high, radial fins the exchanger has an acceptable size while meeting the required pressure drop. This type of heat exchanger is therefore suitable for the given application.

3.5 Banks of tubes with continuous plate fins

This represents a bank of tubes embedded in plate fins. Using this type of fins it is possible to use tubes of a smaller diameter and thus enlarge the flow area and the heat transfer area. This type of geometry results in small size of the heat exchanger at pressure drop significantly lower than the allowed value. Flue-gas flows around the tubes. This type of heat exchanger is therefore applicable for the given application.

Using this type of heat exchanger would be possible to solve engagement in the modular arrangement (i.e. stack more heat exchangers of this type with a smaller number of tubes in a row and have the possibility to regulate the water outlet temperature via changes in size of heat transfer area).

3.6 Plate heat exchanger

This type of heat exchanger is suitable for air heating. When using plain plates and keeping pressure losses below the allowed value, the exchanger is too large. This option is not suitable for the given application.

3.7 Plate heat exchanger with inserts

It is a heat exchanger with smooth plates between which are inserted finned surfaces. Process media flow at the so-called crossflow regime. In this type of heat exchanger has volume smaller than 1 m^3 at a pressure drop well below the allowed value. This type of heat exchanger could also be used for the given application.

4. Conclusions

The article dealt with the selection of suitable types of heat exchangers for low temperature application in a washing unit to increase its thermal efficiency. This can be achieved by utilization of the waste heat contained in flue-gas produced by a microturbine. The recovered heat can be used for heating of process fluids (drying air or water). The heated air will be used as drying air while the heated water will be used in the laundry process. A conventional-type of heat exchanger was used to heat the process media because of its low investment cost.

In order to identify the appropriate heat exchanger type, a large amount of calculations of various types of heat exchangers was carried out. These calculations proved that using heat exchangers without enhanced surfaces is not suitable. This heat exchanger has very high heat transfer area and high pressure loss. It means the investment and operational costs are very high. The most appropriate solution is to use banks of tubes with continuous fins for heating of drying air and tubular heat exchanger with a special type of longitudinal fins or twisted tube heat exchanger for heating of water. In the next stage of research, detail cost analysis of identified feasible types of heat exchangers will be performed. The selected types of heat changers will be manufactured and will be tested in the laboratories of NETME Centre.

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