Applied Thermal Engineering 215 (2022) 118976

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

A Thermal-hydraulic assessment of condensing tube bank heat exchangers for heat and water recovery from flue gas

Negar Mohammadaliha [a], Mohammad Amani [b], Majid Bahrami [a,*]

[a] Laboratory for Alternative Energy Conversion (LAEC), School of Mechatronic Systems Engineering, Simon Fraser University, BC V3T 0A3, Canada
[b] Department of Mechanical Engineering, Arak University of Technology, Arak, Iran

A R T I C L E I N F O

Keywords:
Condensing heat exchanger
Heat and water recovery
Wet flue gas
Heat exchanger design
Thermal conductivity
Latent heat

A B S T R A C T

Condensing heat exchangers are capable of recovering a significant amount of latent heat at temperatures below 100 °C from the flue gas of combustion-based heating systems due to the presence of water vapor in their exhaust streams. However, the condensation of acids along with water vapor creates a highly-corrosive environment in these heat exchangers. As such, a large majority of these heat exchangers are made from corrosion-resistant alloys, such as stainless steel. Polymer-based materials are cost-effective and have great corrosion-resistant properties. Since the performance parameters of a heat and water recovery unit depend on the size and compactness of their heat exchangers, it is challenging to compare the overall performance of stainless-steel condensing heat exchangers with polymeric ones based on the data available in the literature. The main goal of the present study is to develop and assess the thermal–hydraulic performance of a proof-of-concept condensing heat exchanger made of fluorinated ethylene propylene compared to the same condensing heat exchanger made of stainless steel for heat and water recovery from flue gas. For this purpose, an in-depth parametric study is conducted experimentally to evaluate the water recovery efficiency, total heat recovery rate, and pressure drop in the flow paths. The results revealed that the water recovery efficiency of the unit with a specific size, declines when the mass flow rate of the gas increases, although it enhances the total heat recovery of the unit. Moreover, increasing the volumetric flow rate of the heat transfer fluid flow slightly increases the total heat recovery of the stainless-steel condensing heat exchanger, but has a negligible impact on the total heat recovery rate of the polymer-based heat exchanger. Increasing the humidity ratio of the flue gas or the inlet temperature of heat transfer fluid does not have any significant effect on the flue gas pressure drop. These findings are significantly important and novel as they unlock the potential of using polymer-based materials with thermally conductive additives for latent heat recovery from flue gas.

1. Introduction

A significant portion (up to 60%) of the total energy of industrial plants, such as oil and gas, petrochemical, and power plants is released into the environment in the form of low-temperature thermal energy or low-grade waste heat, i.e., with a temperature of less than 175 °C. The flue gas generated from the combustion of fossil fuels or biofuels in the process heating equipment, such as boilers, furnaces, and ovens, is one of the main sources of low-grade waste heat. In Canada, industry accounts for 38% of total energy demand (electric and thermal energy), while 30–40% of the input energy into industrial processes is discharged into the ambient environment as waste heat [1]. However, in China, the largest energy consumer in the world, the industrial sectors' share of the total energy consumption was even higher and around 62%, while around 50% of that energy was released to the ambient environment as waste heat [2]. Fig. 1 shows the portions of the annual energy demands of the countries that are wasted to the ambient environment due to different sources of inefficiencies in the industrial processes. This is a tremendous amount of thermal energy that offers opportunities for harvesting and utilizing it in a wide variety of applications ranging from building air conditioning to greenhouses applications for food production. Therefore, waste heat recovery and utilization especially from low-grade sources will be beneficial for improving energy efficiency and decreasing fossil fuels consumption, greenhouse gas emissions, as well as reducing the release of harmful chemicals into the ambient environment, which are directly linked to climate change and our environmental impact [3,4].

* Corresponding author.
E-mail addresses: m.amani@arakut.ac.ir (M. Amani), mbahrami@sfu.ca (M. Bahrami).

https://doi.org/10.1016/j.applthermaleng.2022.118976
Received 11 February 2022; Received in revised form 20 May 2022; Accepted 5 July 2022
Available online 8 July 2022

Nomenclature

c_p	Specific heat
h_{fg}	Latent heat of vaporization
$\dot{m}$	Mass flow rate
P	Pressure
Q_{max}	Maximum possible heat recovery rate
T	Temperature
$\dot{V}$	Volumetric flow rate
Greek letters	
ρ	Density
ω	Humidity ratio
Abbreviations	
FEP	Fluorinated ethylene propylene
HEX	Heat exchanger
HR	Total heat recovery rate
HRE	Heat recovery efficiency
HTF	Heat transfer fluid
RH	Relative humidity
WRE	Water recovery efficiency
Subscripts	
cond	Condensation
g	Flue gas
HTF	Heat transfer fluid
v	Water vapor

dehumidification method with the existing wet flue gas desulfurization process in a single spraying tower. Mohammadaliha et al. [6] investigated the role of condensing heat exchanger material on the thermal performance of heat and water recovery systems. They indicated a threshold for tube thermal conductivity (~0.75 $Wm^{-1}K^{-1}$), which is a point where further increase does not significantly improve the condensation efficiency. Cui et al. [7] developed a packed tower as a direct contact heat exchanger for energy and water recovery from humid flue gas. They showed that the packed tower had a small resistance and high heat transfer coefficient. Szulc et al. [8] investigated the performance of a pilot-scale heat/water recovery system made of Teflon tubes in a lignite-fired power plant. The total heat recovery rate of the unit was reported to be around 312 kW, in which 60% of it, was the share of latent heat. Xiong et al. [9] built and tested a plastic heat/water recovery system and reported that 80% of the recovered heat came from recovering the latent heat, while the share of sensible heat was only 20%, which clearly showed the significance of latent heat recovery. Zhao et al. [10] showed that the efficiency of the heat recovery process from a natural-gas fired boiler could be enhanced by 10% by implementing an absorption heat pump to further decrease the return temperature of the district heating systems and use it as the heat transfer fluid (HTF) to cool down the flue gas. Li et al. [11] showed that the recovered water from a 300 MW lignite-fired generator, using a flash evaporation and condensation device combined with a heat pump, was enough to run the flue gas desulfurization unit with zero-net water consumption. Prasad et al. [12] used a solar recovery unit based on a silica gel-based desiccant system for recovering drinkable water from atmospheric air. During the daylight, the water content of saturated desiccant was recovered by a solar still. Vandersickel et al. [13] proposed a concept for utilizing an absorption heat pump to recover heat and water in steam-injected gas

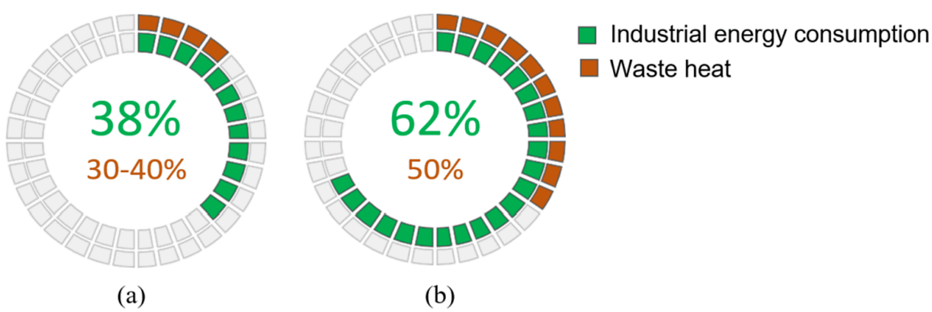

Fig. 1. The share of energy consumption of industrial sectors and their waste heat in the total energy demand of: (a) Canada; and (b) China; circles represent the total annual energy demand of these countries.

Table 1
The types and materials of heat exchangers used for heat and water recovery from flue gas in the literature.

Ref.	Heat exchanger type	Heat exchanger material
[15,16]	In-line tube bank HEXs	Stainless steel
[17]	A vertical tube with a cooling jacket	Stainless steel
[18]	Tube bank HEXs	Stainless steel
[19]	Compact fin-and-tube HEXs	Stainless steel
[20]	Finned tube bank HEXs	Stainless steel
[21]	Staggered and in-line tube bank HEXs	Titanium
[22]	Spiral tube HEXs	Copper
[8]	Shell-and-tube HEXs	Teflon
[9]	In-line tube bank HEXs	PFA
[23]	Spiral plate HEXs	PTFE

Recovering sensible and latent heat from the flue gas of combustion-based heating systems is the main advantage of implementing heat/water recovery units. Chen et al. [5] proposed a novel method for water and heat recovery in flue gas by combining the liquid-desiccant-based

turbines. Full water recovery and increases in fuel efficiency of more than 20% was achieved. Wang et al. [14] proposed the integration of an absorption heat pump and a condensing heat exchanger for recovering waste heat and water from moist flue gas. Based on their results, by reducing the 5 °C flue gas temperature, 44.8% of water consumption in the scrubber could be saved and 81.4 *t/h* water could be recovered.

The different types of heat exchangers designed and tested in the literature for heat and water recovery from flue gas and the materials that the heat exchangers were made of are listed in Table 1. It can be seen that most of the studies in the literature employed heat exchangers made of stainless-steel tubes and that polymer-based condensing heat exchangers are not well-studied. The usage of stainless steel and/or polymers as the material for such heat exchangers are due to the corrosive nature of the flue gas. Since the performance of condensing heat exchangers depends on their size and compactness, it is challenging to compare the performance of stainless-steel heat exchangers with polymer-based ones based on the data available in the literature. Thus, this study aims to investigate the thermal–hydraulic performance of an innovative condensing heat exchanger made of stainless-steel tubes and

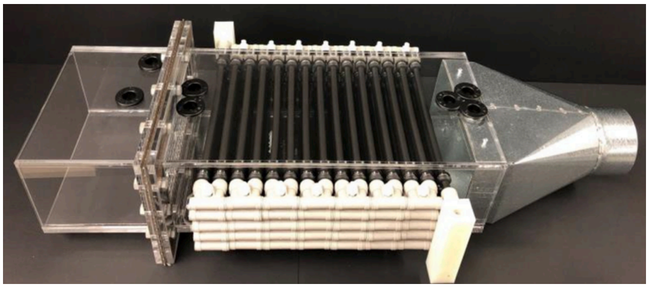

Fig. 2. A custom-built condensing heat exchanger with replaceable tubes made from stainless steel and polymeric FEP materials.

Table 2
The summary of specifications and geometrical parameters of the custom-built condensing heat exchanger made from stainless steel and polymeric FEP materials.

Parameter	Value
Outer tube diameter	9.5 mm
Tube thickness	0.8 mm
Tube length, placed inside the frame	210 mm
Number of tubes – transversal direction	5
Number of tubes – longitudinal direction	15
Tube pitch – transversal direction	21.7 mm
Tube pitch – longitudinal direction	21 mm

fluorinated ethylene propylene (FEP) tubes. For this purpose, an in-depth parametric study is conducted to evaluate the water recovery efficiency, total heat recovery rate, and pressure drop in the flow paths, experimentally. The results of this study reveal the potential of using polymer-based condensing heat exchangers instead of more expensive metallic ones made of stainless steel and titanium, to reduce the cost of heat and water recovery units.

2. Experimental procedure

To further evaluate and compare the performance of condensing heat exchangers made of Fluorinated Ethylene Propylene (FEP) and stainless steel (Grade 304) materials, a lab-scale experimental testbed was designed to investigate the significance and the impact of the heat exchangers material on the thermal performance.

2.1. Experimental facilities

A custom-built condensing heat exchanger with replaceable tubes was designed and built in the Laboratory for Alternative Energy Conversion (LAEC) to examine its heat and water recovery performance over a wide range of operating conditions (see Fig. 2). The main specifications of the unit are listed in Table 2. To make the tubes replaceable, as shown in Fig. 3, push-in u-bends (John Guest, UK) were used to connect the tubes. The bends were placed outside of the frame and were insulated to ensure that there was no heat loss to the ambient environment through them.

The headers distribute the HTF flow equally among five parallel paths and mix them at the outlet. The main advantage of having the custom-designed condensing heat exchanger was the feasibility of changing the tubes while keeping all the other geometrical parameters identical. Moreover, a P-trap was installed on the bottom of the testbed to collect the recovered water and prevent air from entering the unit while allowing the recovered water to pass through the discharge hole on the bottom of the heat exchanger.

A testbed, schematically shown in Fig. 4, was designed and built to measure the thermal and hydraulic performance of the condensing heat exchanger. A temperature control system (FL4003, Julabo) was used to circulate the HTF through the heat exchanger tubes and keep the inlet temperature constant. The inlet and outlet HTF temperatures were measured using two RTD sensors (Pt100, OMEGA) installed before and after the heat and water recovery unit. The HTF flow rate was measured using an oval gear flow meter (OM015S001, FLOMEC) and controlled using a valve. Further, two pressure transmitters (PX305-100 GI, OMEGA) were installed before and after the unit to measure the pressure drop of the HTF flow.

To mimic the flue gas conditions in the lab, an air stream was used and the inlet temperature and humidity ratio were set using a standard environmental chamber (SE-3000–10-10, Thermotron). The chamber is capable of setting the temperature and relative humidity from −70 to + 180 °C and 10–98 %RH, respectively. The gas flow rate was controlled using a variable-speed axial fan. The flow rate of the gas was measured using an orifice plate (Oripac 4150 T, Lambdasquare) mounted inside a circular duct using standard flanges. The orifice plate and the circular ducts connected to both sides of the orifice plate were placed inside the environmental chamber to avoid condensation inside the circular ducts. The pressure drop of the gas passing through the orifice plate was measured using a differential pressure sensor (2671005WB2DA1FD, Setra). Moreover, RTD sensors (Pt100, OMEGA) and the relative humidity sensors (HMP110, Vaisala) were installed before and after the heat exchanger to measure the inlet and outlet temperature and humidity ratio of the gas. Moreover, the gas pressure drop was measured

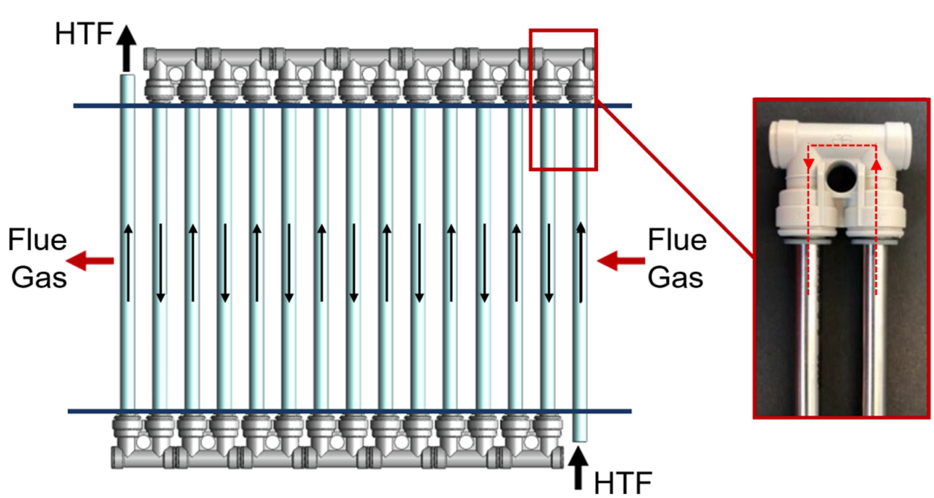

Fig. 3. A schematic showing the flow of the HTF and flue gas through the condensing heat exchanger, where the tubes are connected using reusable push-in u-bends.

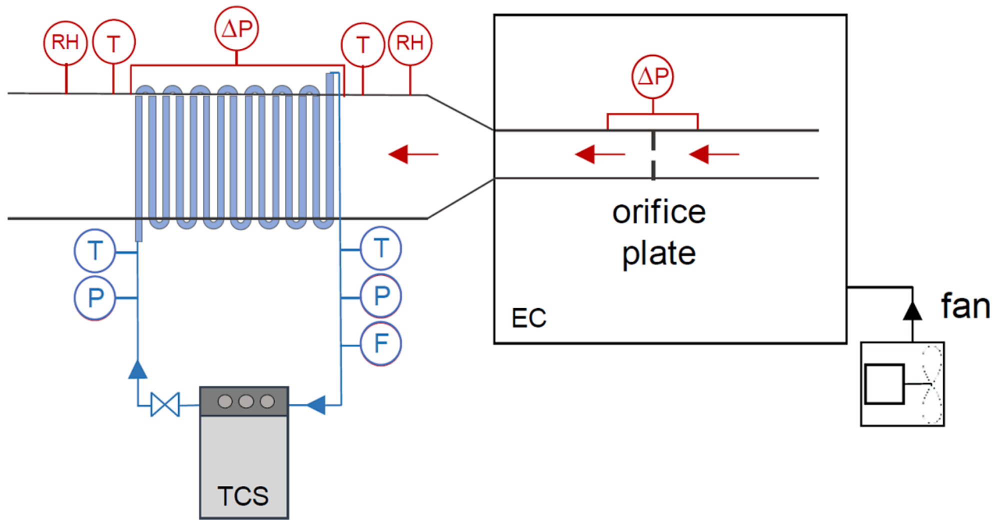

Fig. 4. A schematic of the experimental testbed; blue arrows: HTF flow; red arrows: flue gas flow; EC: environmental chamber; TCS: temperature control system; T: temperature sensor; P: pressure sensor; RH: relative humidity sensor; F: liquid flow meter.

Table 3
The summary of sensors used in the testbed for data measurement.

Sensor	Model	Range	Uncertainty
Temperature sensor	RTD (Pt100) - OMEGA	−200 to 500 °C	0.15 °C
Flow meter	OM015S001- FLOMEC	0 to 40 lit. min^{-1}	0.5%
Pressure transmitter	PX305 - OMEGA	0 to 100 psi	0.25%
Differential pressure sensors	2671005WB2DA1FD - Setra	± 5″W.C	0.25%
	2671R25WB2DA1FN - Setra	± 0.25″W.C	0.25%
Humidity sensor	HMP110 - Vaisala	0 to 100%	3 %RH
Scale	ML4002E, Mettler Toledo	0 to 5000 g	0.01 g

using a differential pressure sensor (2671R25WB2DA1FN, Setra). The mass of the recovered water was measured using a scale (ML4002E, Mettler Toledo). The testbed was insulated to minimize the heat loss to the ambient environment and ensure that the entire recovered sensible and latent heat of gas was transferred to the HTF flow. More details related to the sensors, including their ranges and uncertainties are listed in Table 3.

2.2. Assessment of the testbed insulation

In order to prevent any heat loss to the ambient environment, the testbed was insulated using extruded polystyrene rigid insulation covered by a layer of foam insulation, see Fig. 5a. As shown in Fig. 5b, the image taken from the testbed during the tests using a portable IR camera (i7, FLIR) showed that the surface temperature of the testbed is close to the ambient temperature during the tests in spite of the significant temperature difference between the gas flow and ambient air.

In the case of ideal insulation, heat transfer occurs only between the HTF and the gas flow. In other words, the recovered sensible and latent heat from the gas flow is transferred to the HTF flow, increasing the temperature of the HTF flow. To assess the insulation of the testbed, the balance between the amount of heat gained by the HTF flow and the amount of heat transferred from the gas flow was investigated to ensure that there was no heat loss from the testbed to the ambient environment. For some of the tests conducted in this study, Fig. 6 shows the heat transfer rate of the HTF flow in comparison with the sensible and latent heat recovery rates from the gas flow, for a range of HTF volumetric flow rates. The summary of the test conditions for the Fig. 6 data is listed in Table 4. Moreover, the heat balance was tested for a range of different inlet conditions, see Fig. 7. As shown in Fig. 6 and Fig. 7, there is a proper balance (within the experimental data uncertainty range) between the amount of heat transferred to the HTF flow and the total heat,

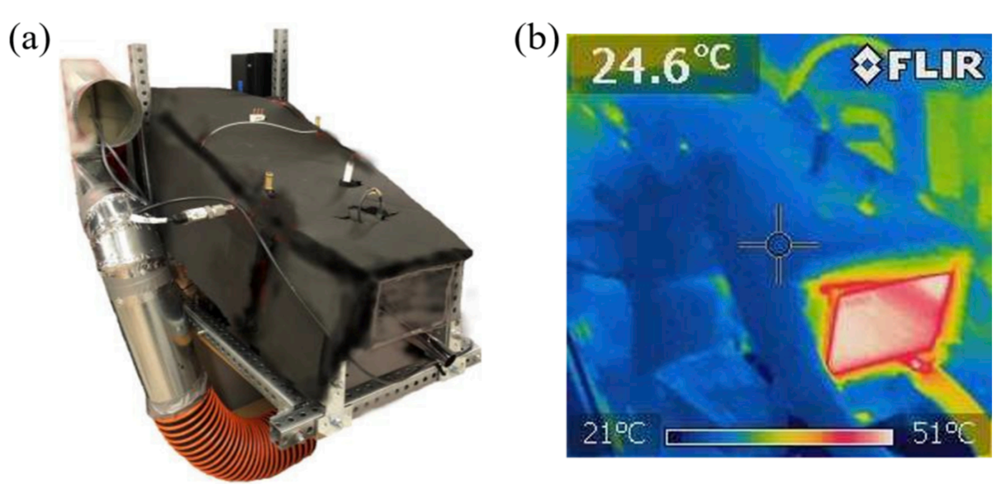

Fig. 5. (a) The experimental testbed after insulation; and (b) an IR image of the testbed during the tests.

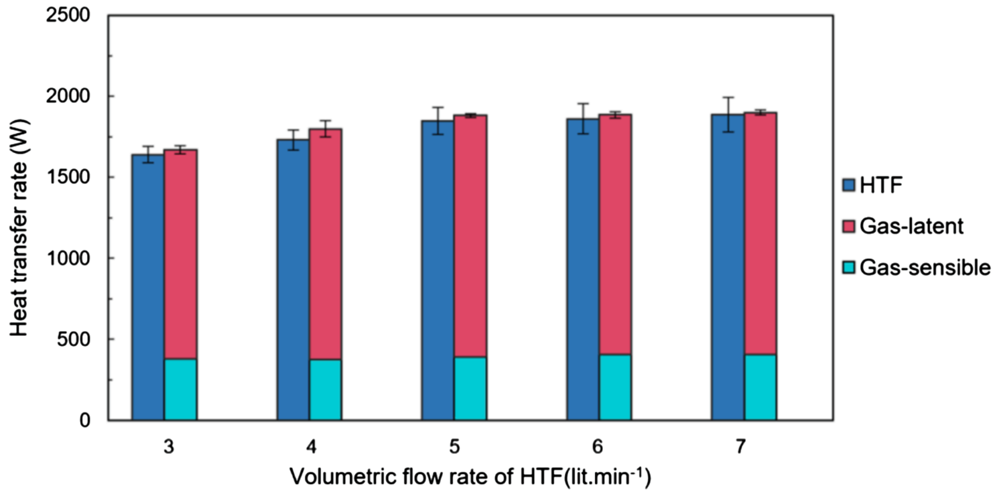

Fig. 6. The balance of heat transfer rates between the gas flow (sensible and latent) heat versus the heat removed by the HTF flow.

Table 4
The summary of the test conditions for the Fig. 6 data.

Tube material	FEP polymer
Inlet HTF temperature	25.0 °C
Inlet gas temperature	70 °C
Mass flow rate of the gas	80 kg•h^{-1}
Volumetric flow rate of HTF	3–7 lit.min^{-1}
Inlet gas humidity ratio	100 $gH_2O/kg_{dry\text{-}air}$

Table 5
Inlet conditions of the baseline along with their variations range defined for the parametric study.

	Baseline condition	Range
Inlet HTF temperature	25 °C	25–35 °C
Inlet gas temperature	70 °C	–
Mass flow rate of the gas	80 kg•h^{-1}	40–100 kg•h^{-1}
Volumetric flow rate of the HTF	5 lit.min^{-1}	3–7 lit.min^{-1}
Inlet gas humidity ratio	100 $gH_2O/kg_{dry\text{-}air}$	50–130 $gH_2O/kg_{dry\text{-}air}$

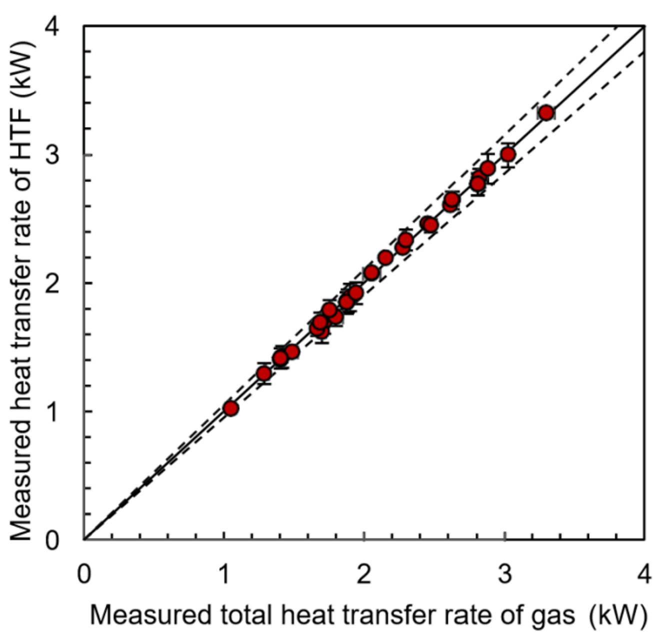

Fig. 7. The measured heat transfer rate of the HTF versus the total heat transfer rate of gas for all the tests.

including both sensible and latent heat, transferred from the gas flow, which indicates the proper insulation of the testbed.

3. Performance metrics

The thermal–hydraulic performance of a condensing heat exchanger is investigated using the key performance indicators as follows:

- Water recovery efficiency (WRE).

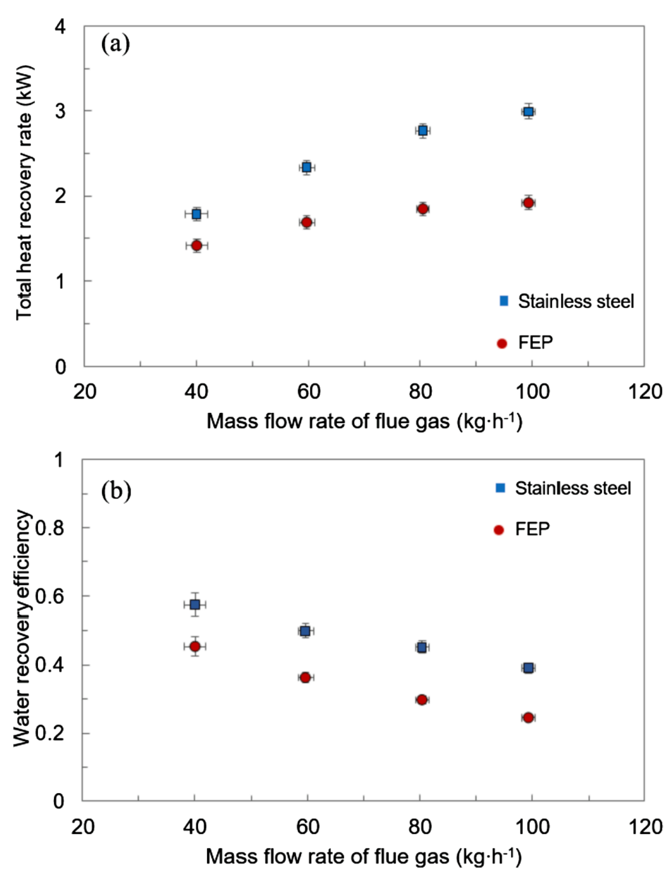

Fig. 8. The variation of: (a) the total heat recovery rate; and (b) the water recovery efficiency with inlet mass flow rate of flue gas, see Table 5 for baseline operating conditions.

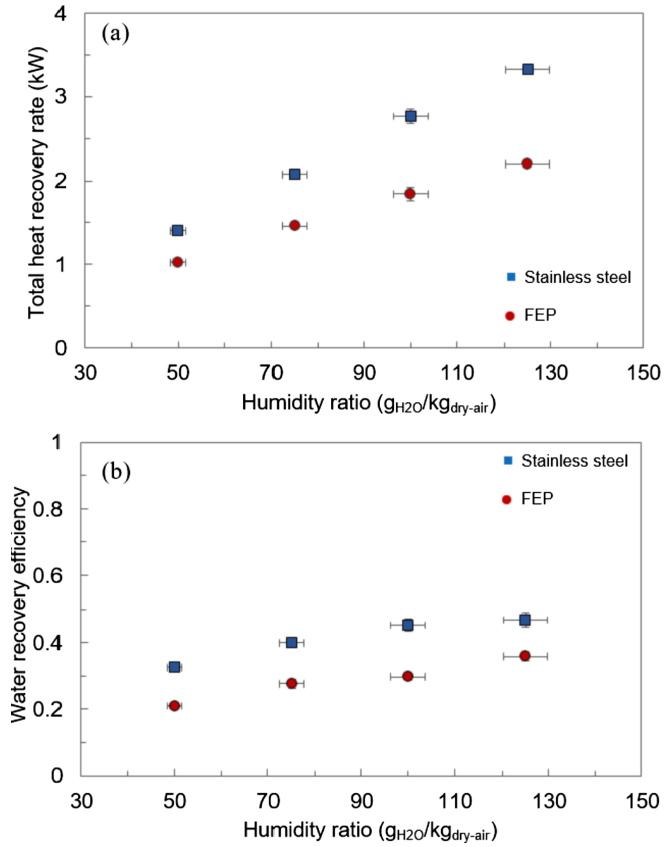

Fig. 9. The variation of: (a) the total heat recovery rate; and (b) the water recovery efficiency with the inlet humidity ratio of the flue gas, see Table 5 for baseline operating conditions.

The water recovery efficiency is defined as the condensation rate ($\dot{m}_{cond}$) over the mass flow rate of water vapor in the flue gas at the inlet of a condensing heat exchanger ($\dot{m}_{v,in}$), which can be calculated by:

$$WRE = \frac{\dot{m}_{cond}}{\dot{m}_{v,in}} \tag{1}$$

In other words, this parameter shows the percentage of water vapor that can be recovered from flue gas using the condensing heat exchanger. Water recovery efficiency also shows the performance of the system in recovering latent heat of flue gas.

- Heat recovery efficiency (HRE).

The heat recovery efficiency is defined as the ratio of the total heat recovery rate over the maximum possible heat recovery rate, which can be computed from Eq. (2).

$$HRE = \frac{\dot{m}_{cond}h_{fg} + \dot{m}_g c_{p,g}\left(T_{g,in} - T_{g,out}\right)}{\dot{m}_{v,in}h_{fg} + \dot{m}_g c_{p,g}\left(T_{g,in} - T_{HTF,in}\right)} \tag{2}$$

where, h_{fg} denotes the latent heat of vaporization, $\dot{m}$ is the mass flow rate, and c_p is the specific heat. Subscripts including g and HFT denote the flue gas and HTF, respectively. The change in the specific heat of the flue gas as a result of the condensation is less than 3% and can be neglected. Heat recovery efficiency assesses both the sensible and latent heat recovery of the unit.

- Total heat recovery rate (HR).

The total heat recovery rate is calculated based on the temperature increase of the HTF as a result of both the sensible and latent heat, recovered from the wet exhaust stream. This parameter can be obtained as follows:

$$HR = \dot{m}_{HTF}c_{p,HTF}\left(T_{HTF,out} - T_{HTF,in}\right) \tag{3}$$

- Flue gas/HTF pressure drop.

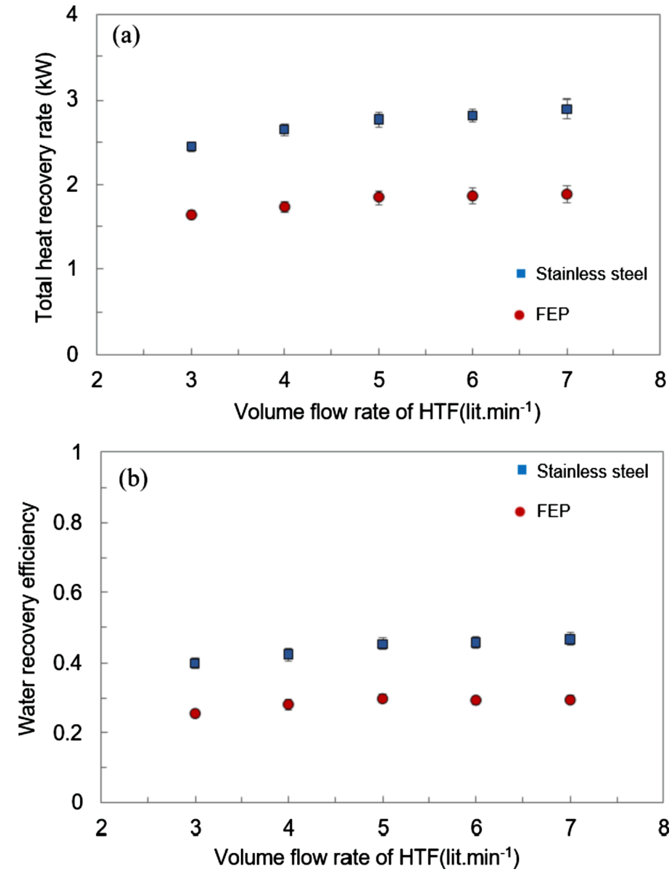

Fig. 10. The variation of: (a) total heat recovery rate; and (b) the water recovery efficiency with the inlet volume flow rate of HTF, see Table 5 for baseline operating conditions.

Pressure drops of both the flue gas flow (ΔP_g) and the HTF flow (ΔP_{HTF}) should be considered to fully assess the performance of a condensing heat exchanger as follows:

$$\begin{cases} \Delta P_g = P_{g,out} - P_{g,in} \\ \Delta P_{HTF} = P_{HTF,out} - P_{HTF,in} \end{cases} \tag{4}$$

It should be noted that it is not desirable to cool down the flue gas to reach the inlet temperature of the HTF flow and recover as it affects the flue gas discharge at the stack. Since the share of the sensible heat is negligible compared to the share of the latent heat, the value of the heat recovery efficiency is close to the value of water recovery efficiency. Therefore, the water recovery efficiency and the total heat recovery rate are considered as the thermal performance indicators.

4. Uncertainty analysis

Due to the measurement accuracy of the sensors and the standard deviation of the readings, there are uncertainties in the measured performance parameters that should be calculated. In this study, we used the standard method developed by Moffat [24].

The total heat recovery rate (HR) is calculated from measurements of RTD temperature sensors and the liquid flow meter. It should be mentioned that the uncertainties of the thermodynamic properties of the

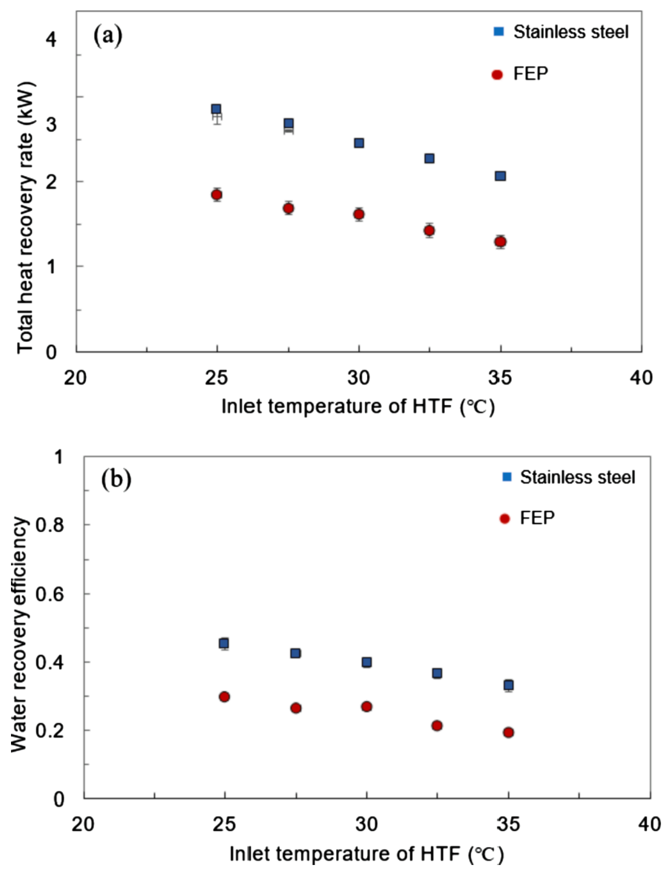

Fig. 11. The variation of: (a) the total heat recovery rate; and (b) the water recovery efficiency with the inlet temperature of HTF, see Table 5 for baseline operating conditions.

HTF, including its density and specific heat, are neglected. Therefore, the uncertainty of the total heat recovery rate (HR) is written as:

$$\left(\frac{\delta HR}{HR}\right)^2 = \left(\frac{\delta\rho}{\rho}\right)^2 + \left(\frac{\delta\dot{V}_{HTF}}{\dot{V}_{HTF}}\right)^2 + \left(\frac{\delta c_{p,HTF}}{c_{p,HTF}}\right)^2 + \left(\frac{\delta\left(T_{HTF,out} - T_{HTF,in}\right)}{T_{HTF,out} - T_{HTF,in}}\right)^2 \quad (5)$$

where, $\dot{V}_{HTF}$ is the volume flow rate of the HTF. Considering the uncertainties of the sensors listed in Table 3 and the values of the parameters, the maximum uncertainty of total heat recovery rate measurements was 9%. The uncertainties of the water recovery efficiency (WRE) and heat recovery efficiency (HRE) are calculated as:

$$\left(\frac{\delta WRE}{WRE}\right)^2 = \left(\frac{\delta\omega}{1+\omega}\right)^2 + \left(\frac{\delta\omega}{\omega}\right)^2 + \left(\frac{\delta\dot{m}_{cond}}{\dot{m}_{cond}}\right)^2 + \left(\frac{\delta\dot{m}_{g,in}}{\dot{m}_{g,in}}\right)^2 \quad (6)$$

$$\left(\frac{\delta HRE}{HRE}\right)^2 = \left(\frac{\delta HR}{HR}\right)^2 + \left(\frac{\delta Q_{max}}{Q_{max}}\right)^2 \quad (7)$$

where, Q_{max} is the maximum possible heat recovery rate and is defined as follows:

$$Q_{max} = \dot{m}_{g,in}\frac{\omega}{1+\omega}h_{fg} + \dot{m}_{g,in}c_{p,HTF}\left(T_{g,in} - T_{HTF,in}\right) \quad (8)$$

To calculate the uncertainty of these parameters, the uncertainty of the gas humidity ratio (ω) at the inlet of the unit should be calculated based on the uncertainty of the readings of humidity and temperature sensors located before the heat exchanger. Considering the uncertainties of the sensors listed in Table 3 and the values of parameters, the maximum uncertainty of water recovery efficiency was estimated at 3.5% for the range of inlet conditions tested in this study.

5. Results and discussion

A comprehensive parametric study was performed to examine the thermal–hydraulic performance of condensing heat exchangers made of stainless-steel (Grade 304) tubes and polymeric FEP tubes with relatively high and low ranges of thermal conductivity of tube materials. The inlet conditions of the baseline case and their variations range are listed in Table 5. Then, each parameter was varied over an arbitrarily chosen range, while all other inlet conditions were kept constant to investigate the effects of each parameter on the performance metrics.

Fig. 8 shows the variation of performance indicators seen when increasing the mass flow rate of the flue gas for both the stainless-steel condensing heat exchanger and the polymeric FEP condensing heat exchanger. Increasing the mass flow rate of the flue gas leads to an increase in the Nusselt number and, consequently, a higher convective heat transfer coefficient for the gas. Therefore, using the Lewis analogy, the mass transfer coefficient of the gas increases which results in a higher condensation rate and, consequently, a higher latent heat recovery rate. Moreover, the sensible heat recovery rate from the gas flow increases due to the lower convective resistance between the gas flow and the tube wall. Therefore, increasing the mass flow rate of the flue gas results in a significant increase in the total heat recovery rate (see Fig. 8a). However, as shown in Fig. 8a, the rate of increase for the stainless-steel condensing heat exchanger is significantly higher than for the polymeric one. The reason behind these trends is the effect of the interface temperature. The interface temperature of the stainless-steel condensing heat exchanger is much lower than for the polymeric one due to the lower resistance of tube wall, which leads to a lower mole fraction of the water vapor on the stainless-steel heat exchanger's interface and a larger difference between the mole fraction of the vapor in the bulk of the gas and the vapor on the interface. Moreover, increasing the mass flow rate of flue gas results in the higher bulk temperature of the flue gas and therefore, a higher interface temperature. Therefore, there is a trade-off between the higher interface temperature and the higher convective heat and mass transfer rate of the gas. Xiong et al. [9] observed a significant reduction in the heat recovery rate of the polymeric heat exchanger with increasing the flue gas velocity within the range of inlet conditions that they considered. All these results show that there is an optimum flue gas flow rate (velocity) to reach the maximum heat recovery rate for a specific set of inlet conditions.

As shown in Fig. 8b, by increasing the mass flow rate of the flue gas, the mass flow rate of the water vapor entering the condensing heat exchanger increases. Although, increasing the mass flow rate of the flue gas leads to enhancement in the condensation rate, it eventually leads to the deterioration of the water recovery efficiency. The reason for this observation is that the augmentation in the mass flow rate of the entering water vapor (in the denominator of the efficiency) is more than the enhancement in the condensation rate (in the numerator of the efficiency). In other words, within the range of inlet conditions considered for the parametric study, the water recovery efficiency of the unit, with a specific size, drops when the mass flow rate of the gas increases, although it enhances the total heat recovery of the unit.

Fig. 9 represents the effect of the flue gas humidity ratio on the total heat recovery rate and the water recovery efficiency of stainless-steel and polymeric FEP condensing heat exchangers. It is worth mentioning that the humidity ratio of the flue gas depends on the type of fuel burning in the boiler. For example, the humidity ratio of 100 g of water vapor per kilogram of dry air approximately corresponds to the flue gas of boilers burning natural gas. A higher humidity ratio of the flue gas corresponds to a higher mole fraction of water vapor in the bulk of the gas. This leads to a larger difference between the mole fraction of water vapor in the bulk of the gas and the interface between the gas and

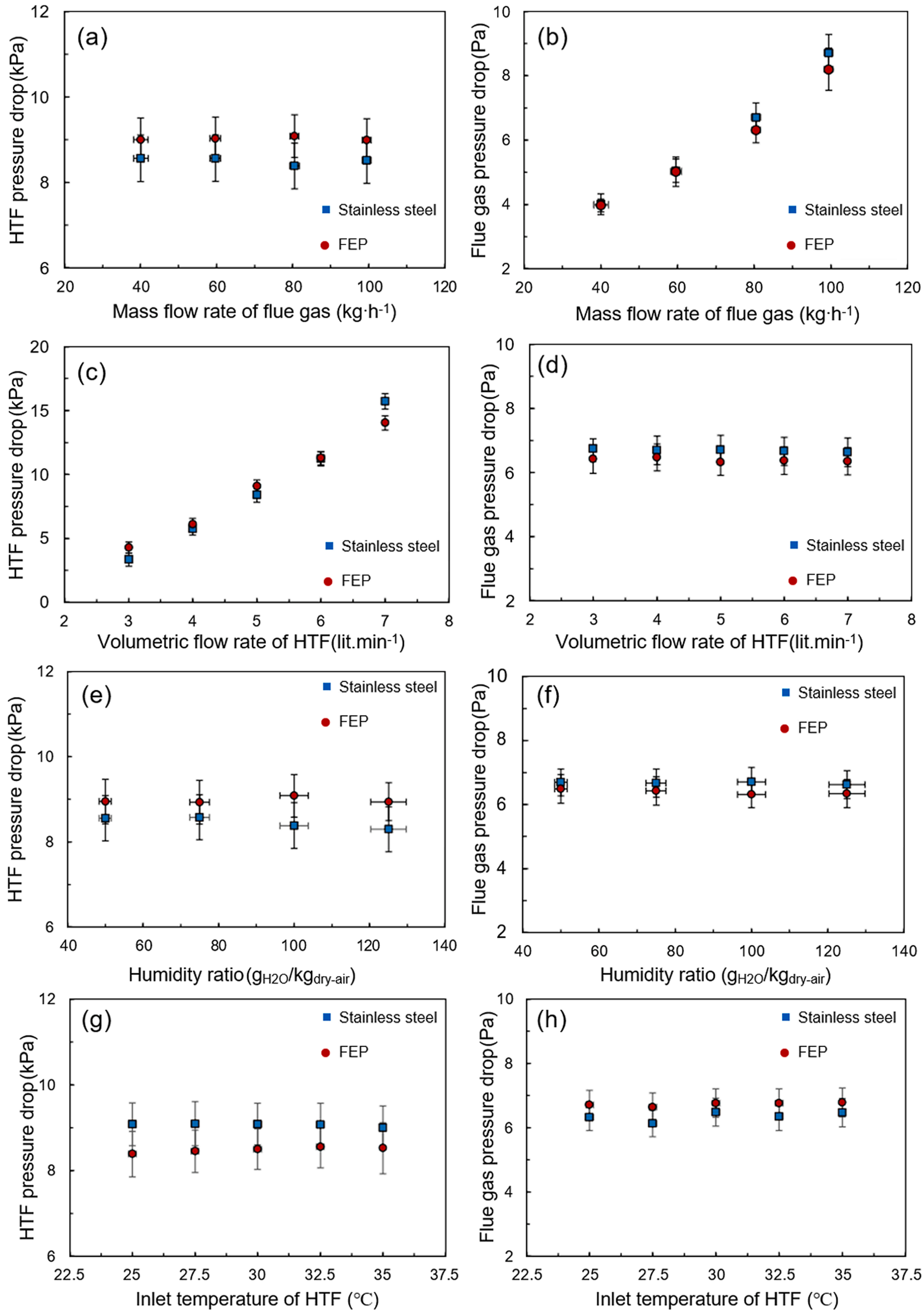

Fig. 12. Comparison of the polymeric and stainless-steel condensing heat exchangers' pressure drops.

the condensate layer. Therefore, as shown in Fig. 9a, the condensation rate and the latent heat recovery rate increases with increasing the inlet humidity ratio of the gas. However, in this case, despite the previous case, the enhancement in the condensation rate (in the numerator of the efficiency) is more than the augmentation in the mass flow rate of the entering water vapor (in the denominator of the efficiency). For this reason, the water recovery efficiencies of both heat exchangers are enhanced by increasing the gas humidity ratio (see Fig. 9b).

Fig. 10 shows the effect of the HTF volumetric flow rate on the total heat recovery rate and water recovery efficiency of the heat exchanger. Increasing the volumetric flow rate of the HTF flow leads to a decrease in the convective heat transfer resistance between the HTF flow and the internal walls of the tubes. As shown in Fig. 10a, this slightly increases the total heat recovery of the stainless-steel heat exchanger but has a negligible effect on the total heat recovery rate of the polymeric heat exchanger. The reason behind this observation could be the higher conductive resistance of the polymeric FEP tubes than the convective heat transfer resistance between the HTF and the internal walls of the tubes in the case of the polymeric heat exchanger. This also leads to an insignificant change in the interface temperature of the polymeric heat exchanger as the convective resistance of the HTF decreases. Since, in this case, the mass flow rate of the water vapor entering the heat exchanger (in the denominator of the efficiency) does not change, the same increasing trends are observed for the water recovery efficiency of condensing heat exchangers (see Fig. 10b).

Fig. 11 shows the variation of the total heat recovery rate and water recovery efficiency of the condensing heat exchangers with the inlet temperature of the HTF. Increasing the inlet temperature of the HTF increases the interface temperature and, consequently, decreases the condensation rate and the total heat recovery rate. As shown in Fig. 11a and 11b, increasing the inlet temperature of the HTF has a more significant effect on the performance of the both heat exchangers compared to increasing the flow rate of the HTF. The main reason for this observation is that increasing the HTF inlet temperature increases the bulk temperature of the HTF, which results in a lower temperature difference and lower heat and water recovery rates.

Fig. 12 shows the effect of inlet conditions on the HTF and flue gas pressure drops in the condensing heat exchangers. The following trends are observed:

- As expected, increasing the gas flow rate does not have any effect on the HTF pressure drop (see Fig. 12a).
- Increasing the flow rate of flue gas results in an increase in the flue gas pressure drop (see Fig. 12b). Xiong et al. [5] also reported that the flue gas pressure drop increased monotonously by increasing the velocity of the flue gas passing through the tube bank heat exchangers.
- Increasing the flow rate of the HTF results in an increase in the pressure drop in the HTF (see Fig. 12c).
- Although, increasing the volumetric flow rate of HTF slightly increases the condensation rate, as shown in Fig. 12d, within the experimental uncertainty range, increasing the volumetric flow rate of HTF flow does not have any significant effects on the gas pressure drop.
- As expected, increasing the humidity ratio of the gas flow or HTF inlet temperature does not have any effects on the HTF pressure drop (see Fig. 12e and 12 g).
- As shown in Fig. 12f and 12 h, increasing the humidity ratio of the flue gas or the inlet temperature of HTF does not have any significant effect on the flue gas pressure drop, despite their impacts on the condensation rates.

6. Conclusion

The conventional metallic heat exchangers (such as those made of stainless steel, copper and aluminum) have disadvantages, such as high cost and weight. Specially treated metallic heat exchangers are required, where the working fluid is highly corrosive. In order to overcome these challenges, polymer-based heat exchangers are investigated. Polymer-based heat exchangers are ideal candidates for heat exchange in chemically-aggressive environments, where conventional metallic heat exchangers fail. With the advantages of greater fouling and corrosion resistance, greater geometric flexibility, ease of manufacturing, and the ability to handle liquids and gases, polymer-based heat exchangers have been widely-studied and used in heat recovery units, micro-electronic cooling devices, and liquid desiccant cooling systems, to name a few. Since the performance parameters of a heat and water recovery unit depend on the size and compactness of their heat exchangers, it is challenging to compare the overall performance of stainless-steel condensing heat exchangers with polymer-based ones based on the data available in the literature. In this study, a custom-built heat and water recovery heat exchanger unit with replaceable tubes was designed to measure the effect of the tubes' material on the thermal–hydraulic performance of condensing heat exchangers. A comprehensive parametric study was conducted experimentally to evaluate the water recovery efficiency, total heat recovery rate, and pressure drop in the flow paths of condensing heat exchangers made of polymeric FEP tubes and results were compared to the same condensing heat exchanger made of stainless steel under various inlet and operating conditions. As expected, the stainless-steel condensing heat exchanger outperformed the polymer-based heat exchanger. The main findings are:

- Increasing the mass flow rate of the flue gas results in a significant increase in the total heat recovery rate, condensation rate, as well as pressure drop, and deterioration of the water recovery efficiency. The rate of increase for the stainless-steel heat exchanger is significantly higher than for the polymeric one.
- The condensation rate and the latent heat recovery rate increase with an increase in the inlet humidity ratio of the gas.
- Increasing the volumetric flow rate of the HTF flow slightly increases the total heat recovery of the stainless-steel heat exchanger but has a negligible effect on the total heat recovery rate of the polymeric condensing heat exchanger.
- Increasing the humidity ratio of the flue gas or the inlet temperature of HTF does not have any significant effect on the flue gas pressure drop, for the range of inlet conditions investigated in this study, in spite of their effect on the condensation rates.

These findings are highly beneficial for the design of polymer-based condensing heat exchangers for latent heat recovery from humid flue gas.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge the financial support of the Natural Sciences and Engineering Research Council of Canada's, College-University Idea to Innovation Grant "*From Waste to Clean Food*" (NSERC CU-I2I Grant No. 501951-16).

References

[1] https://www.nrcan.gc.ca/commercial-industrial-innovation/5493.
[2] H. Lu, L. Price, Q. Zhang, Capturing the invisible resource: Analysis of waste heat potential in Chinese industry, Appl. Energy. 161 (2016) 497–511, https://doi.org/10.1016/j.apenergy.2015.10.060.
[3] A. Mahmoudi, M. Fazli, M.R. Morad, A recent review of waste heat recovery by Organic Rankine Cycle, Appl. Therm. Eng. 143 (2018) 660–675, https://doi.org/10.1016/j.applthermaleng.2018.07.136.
[4] H. Ma, N. Liang, N.a. Zhang, X. Luo, C. Hou, G. Wang, Simulation of a novel waste heat recovery system with sulfide-containing flue gas, Appl. Therm. Eng. 187 (2021) 116556, https://doi.org/10.1016/j.applthermaleng.2021.116556.
[5] Z. Chen, C. You, H. Wang, N. Xie, A novel technical route based on wet flue gas desulfurization process for flue gas dehumidification, water and heat recovery, Appl. Therm. Eng. 171 (2020) 115102, https://doi.org/10.1016/j.applthermaleng.2020.115102.
[6] N. Mohammadaliha, M. Amani, M. Bahrami, Thermal performance of heat and water recovery systems: Role of condensing heat exchanger material, Clean. Eng. Technol. 1 (2020) 100024, https://doi.org/10.1016/j.clet.2020.100024.

[7] Z. Cui, Q. Du, J. Gao, R. Bie, D. Li, Development of a direct contact heat exchanger for energy and water recovery from humid flue gas, Appl. Therm. Eng. 173 (2020) 115214, https://doi.org/10.1016/j.applthermaleng.2020.115214.
[8] P. Szulc, T. Tietze, K. Wójs, Studies on the process of recovering low-temperature waste heat from a flue gas in a pilot-scale plant, Chem. Process Eng. 37 (2016) 529–543, https://doi.org/10.1515/cpe-2016-0043.
[9] Y. Xiong, H. Tan, Y. Wang, W. Xu, H. Mikulčić, N. Duić, Pilot-scale study on water and latent heat recovery from flue gas using fluorine plastic heat exchangers, J. Clean. Prod. 161 (2017) 1416–1422, https://doi.org/10.1016/j.jclepro.2017.06.081.
[10] X. Zhao, L. Fu, W. Yuan, F. Li, Q. Li, The Potential and Approach of Flue Gas Waste Heat Utilization of Natural Gas for Space Heating, Procedia Eng. 146 (2016) 494–503, https://doi.org/10.1016/j.proeng.2016.06.380.
[11] Y. Li, M. Yan, L. Zhang, G. Chen, L. Cui, Z. Song, J. Chang, C. Ma, Method of flash evaporation and condensation – heat pump for deep cooling of coal-fired power plant flue gas: Latent heat and water recovery, Appl. Energy. 172 (2016) 107–117, https://doi.org/10.1016/j.apenergy.2016.03.017.
[12] A. Rajendra Prasad, V. Jaiganesh, S. Sunil Babu, A.M. Shanawaz, T. Vijay Muni, V. Venkatesh, R. Subbiah, Performance of solar still powered water recovery system from moist air, Mater. Today Proc. 62 (2022) 1765–1769, https://doi.org/10.1016/j.matpr.2021.12.336.
[13] A. Vandersickel, W.G. Wedel, H. Spliethoff, High temperature heat and water recovery in steam injected gas turbines using an open absorption heat pump, Appl. Therm. Eng. 165 (2020) 114663, https://doi.org/10.1016/j.applthermaleng.2019.114663.
[14] X. Wang, J. Zhuo, J. Liu, S. Li, Synergetic process of condensing heat exchanger and absorption heat pump for waste heat and water recovery from flue gas, Appl. Energy. 261 (2020) 114401, https://doi.org/10.1016/j.apenergy.2019.114401.
[15] E. Levy, H. Bilirgen, K. Jeong, M. Kessen, C. Samuelson, C. Whitcombe, Recovery of Water from Boiler Flue Gas, Pittsburgh, PA, and Morgantown, WV (2008), https://doi.org/10.2172/952467.
[16] K. Jeong, M.J. Kessen, H. Bilirgen, E.K. Levy, Analytical modeling of water condensation in condensing heat exchanger, Int. J. Heat Mass Transf. 53 (11-12) (2010) 2361–2368, https://doi.org/10.1016/j.ijheatmasstransfer.2010.02.004.
[17] L.i. Jia, X. Li, J. Sun, X. Peng, An experimental study on latent heat recovery of exhaust wet flue gas, J. Therm. Sci. 11 (2) (2002) 144–147, https://doi.org/10.1007/s11630-002-0035-z.
[18] S.K. Hong, S.-i. Park, S.-Y. Jeon, K.-S. Lee, Experimental study on heat transfer characteristics of water-spray-bed heat exchanger, J. Mech. Sci. Technol. 29 (5) (2015) 2243–2247, https://doi.org/10.1007/s12206-015-0445-y.
[19] X. Shi, D. Che, B. Agnew, J. Gao, An investigation of the performance of compact heat exchanger for latent heat recovery from exhaust flue gases, Int. J. Heat Mass Transf. 54 (1-3) (2011) 606–615, https://doi.org/10.1016/j.ijheatmasstransfer.2010.09.009.
[20] H.M. Liu, M.Q. Chen, L. Jia, Condensation Characteristics of Flue Gas/Steam Mixtures with Fine Lignite and Ash Particles along Horizontal Finned Tube Bundles, Exp. Heat Transf. 28 (6) (2015) 580–592, https://doi.org/10.1080/08916152.2014.945053.
[21] K. Hwang, C.h. Song, K. Saito, S. Kawai, Experimental study on titanium heat exchanger used in a gas fired water heater for latent heat recovery, Appl. Therm. Eng. 30 (17-18) (2010) 2730–2737, https://doi.org/10.1016/j.applthermaleng.2010.07.027.
[22] A. Macháčková, R. Kocich, M. Bojko, L. Kunčická, K. Polko, Numerical and experimental investigation of flue gases heat recovery via condensing heat exchanger, Int. J. Heat Mass Transf. 124 (2018) 1321–1333, https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.051.
[23] L. Jia, X.F. Peng, J.D. Sun, T.B. Chen, An experimental study on vapor condensation of wet flue gas in a plastic heat exchanger, Heat Transf. Res. 30 (7) (2001) 571–580, https://doi.org/10.1002/htj.10000.
[24] R.J. Moffat, Contributions to the Theory of Single-Sample Uncertainty Analysis, J. Fluids Eng. 104 (1982) 250–258, https://doi.org/10.1115/1.3241818.