EVALUATION OF HEAT TRANSFER CORRELATIONS FOR FLOW CONDENSATION IN PLATE HEAT EXCHANGERS AND THEIR IMPACT ON THE DESIGN OF ORGANIC RANKINE CYCLE SYSTEMS

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ABSTRACT

A well-verified heat transfer correlation to predict the thermal performance of flow condensation is essential for optimal condenser design in organic Rankine cycle systems. This paper aims at evaluating the prediction accuracy of existing correlations for the flow condensation in plate heat exchangers, and studying the impact of using different correlations for the design and performance estimation of organic Rankine cycle units. In order to achieve these goals, an experimental test campaign was conducted with the working conditions that commonly prevail in condensers of organic Rankine cycle units, and the test data were subsequently utilized for comparison with the predicted values calculated using existing correlations. Moreover, a simulation framework was applied for a case study of waste heat recovery. The results indicate that the correlations from Yan et al. (1999) show best predictive performance to the test data, resulting in a mean absolute percentage deviations below 20 %. With respect to the case study, the required heat transfer area for the plate condenser ranged from 75.8 m^2 to 132 m^2, and the estimated power output of the unit, for a given condenser design, varied in the range -7.2 % to +8 % compared to the target value. The results hence indicate the need for more accurate prediction methods and generally applicable heat transfer correlations.

1. INTRODUCTION

Plate heat exchangers (PHEs) are commonly used as evaporators and condensers in small-scale organic Rankine cycles (ORCs) plants due to their effectiveness and compactness. A general heat transfer correlation capable of predicting the heat transfer coefficient of flow boiling and condensation in PHEs is essential for modeling and designing evaporators and condensers. Compared with the research works on evaporation, there is a limited amount of studies investigating flow condensation in PHEs, making it challenging to develop a well-verified heat transfer correlation for performance prediction (Amalfi et al., 2015). The empirical correlations developed based on experimental data, are currently applied as the prediction models for condenser design in ORC modelling. However, a previous study by Zhang et al. (2019) indicated a weak predictive performance of existing correlations when used for evaluating the heat transfer coefficient for working conditions or working fluids outside the ranges for which the correlations were developed.

An experimental campaign was carried out in this study to obtain a dataset of experimental data for PHE flow condensation in the working conditions that typically prevail in the condenser of ORC plants. The predictive performance of five existing correlations was evaluated for the test points in the database. Moreover, a simulation framework combining a zero-dimensional ORC model (Andreasen et al., 2014) with a PHE condenser model discretized in one-dimension (Mancini et al., 2018), was used to investigate the impact of using alternative condensation heat transfer correlations on the attainable power output from an ORC unit, and on the required heat transfer area for its condenser.

The heat transfer correlations from Yan et al. (1999), Han et al. (2003), Kuo et al. (2005), Longo et al. (2015) and Zhang et al. (2019) were considered in the study. In a previous study, Tao and Ferreira (2019) evaluated the accuracy of existing condensation heat transfer correlations for PHEs against a large database from several studies, and concluded that the correlation from Longo et al. (2015) was the most accurate, predicting 93 % of the experimental data with an accuracy of ± 50 %. The correlation from Kuo et al. (2005) was found to be the second best, predicting 88.4 % of the data within ± 50%. The Yan et al. (1999) correlation predicted 54.2 % of the data within ± 50 %, while the Han et al. (2003) correlation was indicated to underestimate the heat transfer coefficient. Furthermore, a literature survey indicated that the first four correlations are the most widely used for the design of condensers of ORC systems. In addition, the correlation from Zhang et al. (2019) was developed based on a wide range of experimental tests covering the working conditions in condensers of ORC and heat pump systems. However its prediction accuracy was not evaluated in the study performed by Tao and Ferreira (2019).

The main novel contributions of the paper are the following: i) an evaluation of the predictive performances of existing condensation heat transfer correlations for PHEs based on an experimental database particularly developed for the ORC application, and ii) an evaluation of the impact of using different condensation heat transfer correlations on the design and performance estimation of ORC systems.

2. Methods

2.1 Experimental methods

2.1.1 Test facility: A test facility was built at the Technical University of Denmark, which consists of three fluid loops, i.e. one primary working fluid cycle and two auxiliary loops (thermal oil system and cooling water system), used to evaporate and condense the working fluids, respectively. In the main loop, a commercial brazed PHE was used as the condenser (test section). It comprises 16 plates in total, with a length of 317 mm, a width of 76 mm and a hydraulic diameter of 3.4 mm. The details of the test facility and PHE geometry can be found in a previous work (Zhang et al., 2019).

2.1.2 Working conditions: Seven commonly studied working fluids in ORC systems were selected for the testing: three hydrofluorocarbons (R134a, R236fa and R245fa), two hydrofluoroolefins (R1234ze(E) and R1233zd(E)), and two hydrocarbons (propane and isobutane). For each fluid, experimental measurements were acquired for the saturation temperatures 30 °C, 40 °C and 50°C, representing typical condensation temperatures in ORC systems (Bao and Zhao, 2013) and for mass fluxes ranging from 12 kg/m^{2}s to 83 kg/m^{2}s. At the inlet to the condenser the degree of superheat was within 5 K and hence the heat transfer rate in the desuperheating region accounts only for a small fraction (1.1 % – 4.8 %) of the heat transfer rate of the whole condensation process. At the outlet of the condenser the working fluids were almost saturated liquid with a vapor quality between 0 and 0.05.

2.1.3 Data reduction and uncertainties analysis: The method of data reduction is based on Zhang et al. (2018). The temperature measurement uncertainty is ±0.19 K. The errors associated with the mass flow rate and volume flow rate are ±0.015 % and ±0.5 %, respectively. The uncertainties of condensation heat transfer coefficients (h) range between 3.7 % and 14.7 %.

2.2 Simulation framework

The impact of using different condensation heat transfer correlations on the design and performance estimation of ORC units was evaluated for a waste heat recovery case, where the ORC unit is harvesting heat from the jacket cooling water of a marine engine. The data for the heat source and sink were based on the PilotORC case study (Haglind et al., 2017). A simple non-recuperated ORC configuration was investigated. The simulation framework, developed in Matlab (MathWorks, 1994), included models for the ORC unit and the PHE condenser. The thermodynamic properties of the ORC working fluid were retrieved using REFPROP 10 (Lemmon et al., 2018), while those of the heat source and sink were estimated using Coolprop 6.2.1 (Bell et al., 2014).

2.2.1 PHE models: The performance of the PHE condenser was estimated by utilizing previously developed and validated one-dimensional PHE models discretized along the flow direction. The PHE design models are described in Mancini et al. (2018), while the PHE rating models are described in Mancini et al. (2019a). The PHE design model was employed to estimate the minimum required heat transfer area required for the ORC condenser. The PHE rating models were employed to estimate the performance of a specific condenser design as a function of the selected heat transfer correlation. In all cases, the correlation from Zhang et al. (2018) was used to estimate the working fluid pressure drops.

2.2.2 ORC models: The ORC design model previously described and validated in Andreasen et al. (2014) was used in this paper. The power requirements for the pumps suppling the hot and cold fluids were neglected in the study, and therefore the ORC net power output ($\dot{W}_{net}$) was calculated as

$$\dot{W}_{\text{net}} = \dot{W}_{\text{exp}}\, \eta_{\text{gen}} - \dot{W}_p \,, \tag{7}$$

where $\dot{W}_{\text{exp}}$, $\dot{W}_p$, and η_{gen} are the power output from the turbine, the power consumption of the pump, and the efficiency of the electric generator. Table 1 lists the fixed parameters, which were considered for the ORC unit, the PHE condenser, the heat source and sink.

Table 1. Fixed case study parameters

Heat source		**Heat sink**	
Inlet temperature (°C)	85	Inlet temperature (°C)	18.5
Mass flow rate (kg/s)	35	Mass flow rate (kg/s)	35
ORC unit		**PHE condenser**	
Working fluid	R245fa	Port diameter (plate width < 0.25) (m)	0.015
Condenser sub-cooling (°C)	6.5	Port diameter (plate width ≥ 0.25) (m)	0.05
Turbine isentropic efficiency	0.91	Chevron angle (°)	25
Pump isentropic efficiency	0.3	Thermal conductivity (W/m K)	16.2
Generator efficiency	0.98	Corrugation thickness (m)	0.0005

The estimation of the ORC performance during off-design operation was estimated by employing the ORC off-design model described in Baldasso et al. (2019), which was validated against the experimental data collected during the PilotORC project (Haglind et al., 2017). The ORC off-design model was here upgraded to include the PHE condenser rating model (Mancini et al., 2019a).

2.2.3 Optimization of PHE design: Figure 1 shows a sketch of the two-step optimization procedure that was used to estimate the impact of using different heat transfer correlations on the design of the ORC condenser. In the first step, the ORC design was optimized to maximize the attainable net power output. As a first estimate, the heat exchangers were sized by fixing their minimum pinch point temperature difference, and by neglecting their pressure drops.

In the second step, the PHE condenser was designed using the models described in section 2.2.1 and the ORC power output was recalculated by accounting for the working fluid pressure drop in the condenser. During this second step, the required PHE heat transfer area was minimized, while imposing that the ORC power output did not decrease by more than 2 % compared to the ideal case where the pressure drops were neglected. A similar approach was previously described by Mancini et al. (2019b) for a heat pump system. The optimization procedure was carried out by using a combination of particle swarm (200 individuals, 20 iterations) and pattern search (100 iterations) optimizers, both available in Matlab. Table 2 lists the optimization parameters and constraints used for the ORC unit and condenser.

Table 2. Optimized parameters and constraints

ORC unit	
Max pressure (kPa)	100 - 0.8 P_{crit}
Superheating degree (°C)	6.5 – 25
Condensation temperature (°C)	30 – 50
Source outlet temperature (°C)*	>60
Minimum pinch point (°C)*	10
PHE condenser	
Plate width (m)	0.015 – 0.040
Number of channels (-)	25 – 200
Corrugation pitch (m)	0.002 – 0.005
Corrugation pitch - height ratio	1 – 4
Plate width to length ratio*	1.5 – 5
Working fluid inlet velocity (m/s)*	< 4
ORC performance drop*	< 2 %

**constraint*

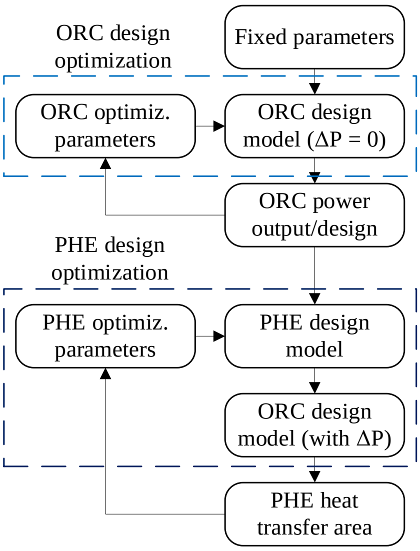

Figure 1. Optimization sketch

2.2.4 ORC off-design performance: An investigation aimed at assessing the impact of using different heat transfer correlations on the predicted performance of an ORC unit featuring a defined condenser design was carried out. The estimations were based on the ORC PHE condenser designs attained by the approach described in section 2.2.3. The expected ORC power output and condensation pressure for each condenser design were estimated by using the ORC off-design model, and by varying the condensation heat transfer correlation used to estimate the performance of the condenser. In all cases, the characteristics of the heat source and sinks (temperatures and flow rates) were kept constant.

3. Results

3.1 Predictive performance evaluation

A parameter, mean absolute percentage deviation (MAPD), is used to quantify the average deviation between the predicted and experimental values:

$$\mathrm{MAPD} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{data_{i,pred}-data_{i,exp}}{data_{i,exp}}\right| \times 100\%. \tag{5}$$

where the $data_{i,pred}$ and $data_{i,exp}$ are the predicted values calculated by the correlations and experimental values, respectively. Figure 2 depicts a comparison of the experimental and predicted values of the heat transfer coefficient using the five correlations. The Yan et al. (1999) and Longo et al. (2015) correlations provide the best and second best predictions with the MAPDs of 15.8 % and 24.6 %, respectively. However, both correlations provide a weak prediction for the two HFOs, R1233zd(E) and R1234ze(E). The Zhang et al. (2019) correlation provides the good predictions for all working fluids but fail to predict the heat transfer coefficient of propane and isobutane. This may be attributed to the fact that the properties of these two fluids (such as densities of vapor and liquid phase) are quite different from the working fluids involved in the database used to develop the correlation. The Han et al. (2003) and Kuo et al. (2005) correlations underestimate the most of the experimental results, with MAPDs of 56.0 % and 39.3 % respectively.

3.2 Condenser and ORC design

Table 3 shows the results of the ORC and condenser optimization procedure. The estimated surface area for the PHE condenser varies between 75.8 m^2 and 132 m^2, depending on the chosen heat transfer correlation. The largest area is found when using the correlation from Kuo et al. (2005), while the lowest is obtained when using the correlation from Longo et al. (2015). The correlations by Yan et al. (1999)

and Zhang et al. (2019) lead to similar area requirements.

In all cases, the optimized solutions featured the maximum allowed number of channels and refrigerant velocity at the inlet of the condenser. The heat transfer area of the condensation section of the condenser represents from 77 % to 89 % the overall heat transfer area, and is the section whose area is directly affected by the selected heat transfer correlation. The differences in the estimated areas for the desuperheating/subcooling sections are due to the different pressure profiles in the various designs.

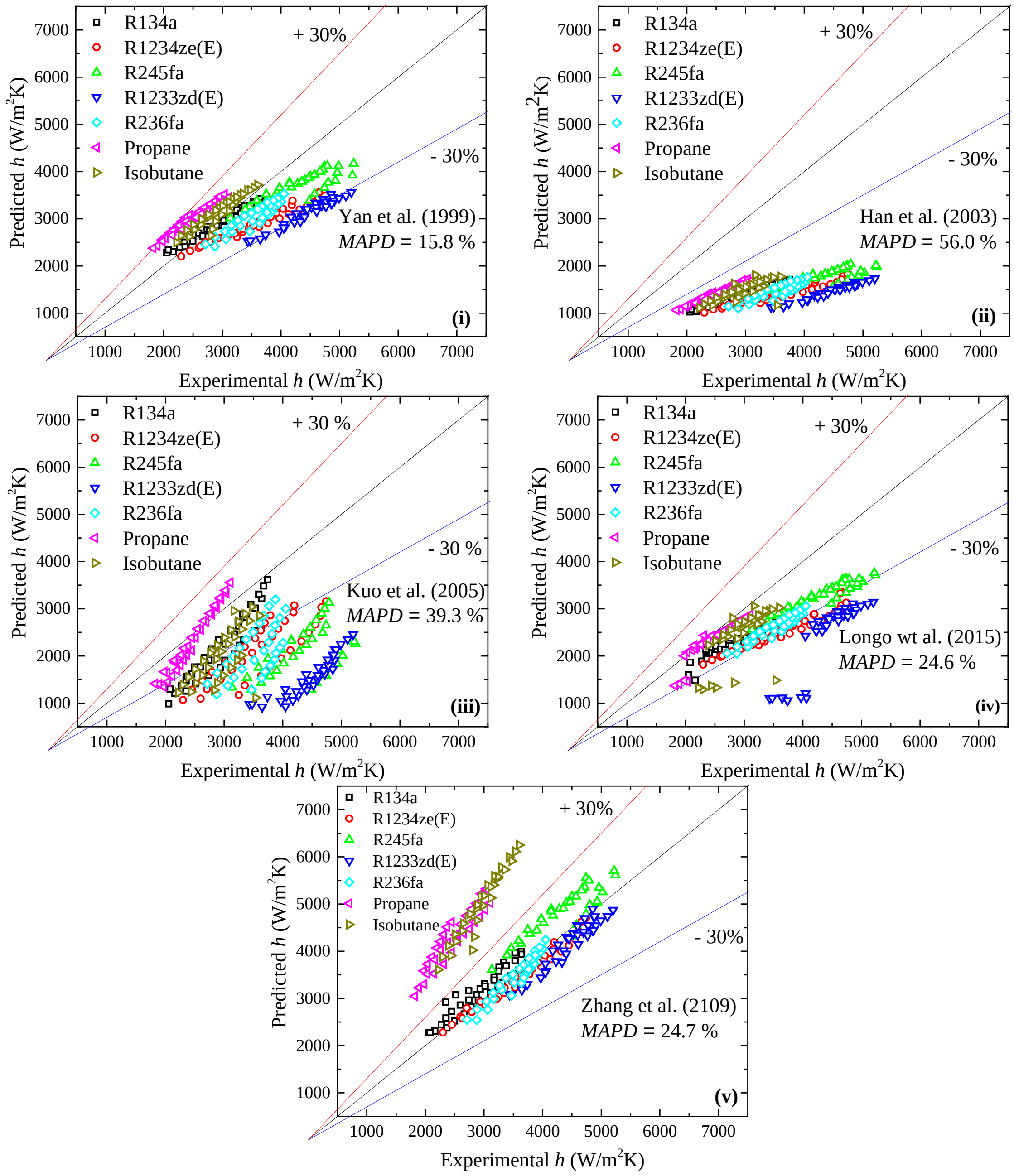

Figure 2. Predicted heat transfer coefficients using different correlations versus the experimental results.

Figure 3 depicts the variation of refrigerant heat transfer coefficient in the optimized condensers. It is possible to notice how the correlation from Kuo et al. (2005) largely underestimates the heat transfer coefficient compared to the other correlations. Significant differences appear also for the other correlations, i.e. the heat transfer coefficient estimated using Longo et al. (2015) is in average 40 %

higher than the one estimated using Yan et al. (1999). Nevertheless, these differences are less marked when looking at the required heat transfer areas (see Table 3). This is mostly because the differences in condensation heat transfer coefficient are smoothened by the contribution of the sink side, which was found to have an average heat transfer coefficient of 6500 W/m^2 K.

Table 3. Results of the ORC design optimization for the various heat transfer correlations

Correlation	Yan et al. (1999)	Han et al. (2003)	Kuo et al. (2005)	Longo et al. (2015)	Zhang et al. (2019)
A_{tot} (m^2)	85.4	78.4	132	75.8	83.8
$A_{desuperheater}$ (m^2)	13.11	13.26	12.59	13.36	13.11
$A_{subcooler}$ (m^2)	3.95	4.01	1.96	4.05	3.95
$A_{condensation}$ (m^2)	68.29	61.09	117.06	58.39	66.73
Plate width (m)	0.35	0.34	0.40	0.34	0.34
Plate length (m)	0.53	0.51	0.70	0.50	0.52
Length/width	1.5	1.5	1.8	1.5	1.5
Number of channels	200	200	200	200	200
Chevron angle	35	35	35	35	35
Pressure drop of working fluid (kPa)	19.2	17.3	29.4	16.2	18.3
Inlet velocity of working fluid (m/s)	4.0	4.0	4.0	4.0	4.0
Pressure drop of sink (kPa)	10.4	9.77	14.7	9.58	10.2
Inlet velocity of sink (m/s)	0.21	0.21	0.21	0.21	0.21
$\dot{W}_{net}$ (kW)	105.0	105.0	104.7	105.0	105.0

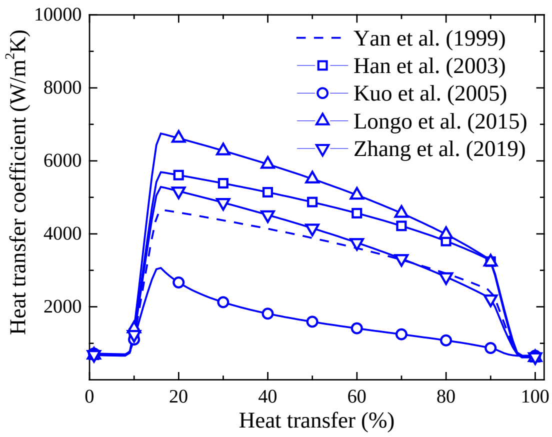

Figure 3. Refrigerant heat transfer coefficient profile in the optimized condenser designs.

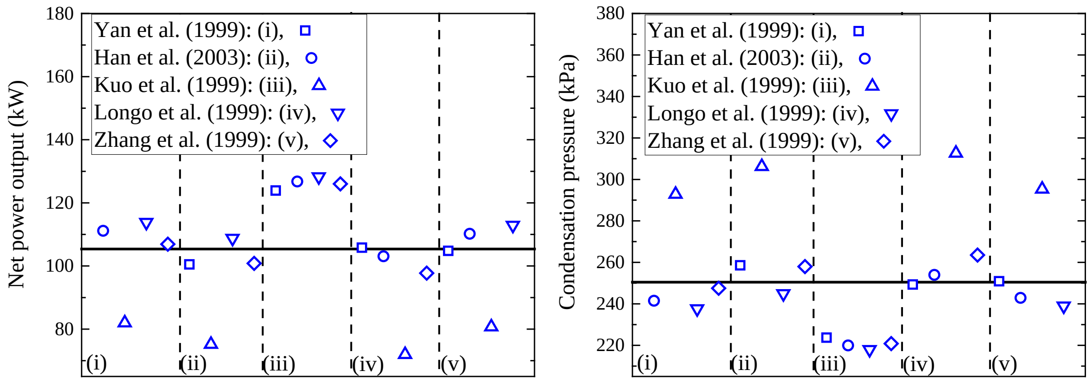

Figure 4. Impact of heat transfer correlation on: a) net power output; b) condensation pressure. The solid lines represent the expected design values, the vertical dotted lines separate solutions attained using condensers designed using the various correlations (indicated by roman numbers), and the marker

shapes indicate the correlations used in the off-design model.

Figure 4 shows the impact of using different heat transfer correlations when estimating the performance of an ORC unit with a given condenser design. The results suggest that both the ORC power output and condensation pressure are highly affected by the heat transfer correlation, which is selected to estimate the unit performance. The highest deviations appear when considering the correlation by Kuo et al. (2005), because its predicted heat transfer coefficients largely deviate from the ones estimated when using the other correlations (see Figure 3). Nevertheless, even when neglecting the solutions connected to the correlation from Kuo et al. (2005), the estimated ORC power output varies between -7.2 % and +8 % compared to the target design value, when changing the heat transfer correlation selected to estimate the condenser performance. The large variations in ORC power output indicate that there is a need for a more accurate condensation heat transfer correlation suitable for ORC conditions, which would enable the correct sizing of the condenser unit.

4. DISCUSSION

The evaluation results of the heat transfer correlations differ to a certain extent between this study and Tao and Ferreira, 2019. One of the example is that Yan et al. (1999) and Longo et al. (2105) correlations respectively have best prediction in the two studies. The discrepancy in evaluation results may be attributed to the difference in the databases. A large database of 2376 data points collected from 30 published research works was developed by Tao and Ferreira (2019), while the 237 data points used in this study focus on the working conditions occurring in condensers of ORC units. Generally, the database in this study has a wider range of mass fluxes and a higher saturation temperature (up to 50 °C). The contradiction in evaluation results indicates that there is a need to develop a heat transfer correlation tailored specifically for the conditions prevailing in condensers of ORC systems.

The investigation on the impact of the selected condensation heat transfer correlation on the design of ORC units was based on a single working fluid and condenser design strategy. More investigations would be required to understand whether other design criteria or working fluids are similarly affected by the choice of heat transfer correlation. Lastly, the differences in the predicted ORC performance could be partially mitigated by varying the sink flow rate to mantain a constant condensation pressure in the ORC. This possibility was not considered in this study. Such analysis would also need to include the cooling water pumping power, which would vary if the sink flow rate is adjusted.

5. CONCLUSIONS

Based on the 237 data points of flow condensation heat transfer in a plate heat exchanger obtained in this study, the results suggest that the Yan et al. (1999) correlation shows best prediction with a mean absolute percentage deviation of 15.8 %. The results of the case study investigations indicated that the use of alternative heat transfer correlations for condensation in plate heat exchangers affected both the estimated condenser heat transfer area (during the organic Rankine cycle design process), and the predicted unit's performance (during the performance estimation process, when the condenser geometry is fixed).

NOMENCLATURE

A	heat transfer area	(m^2)
h	condensation heat transfer coefficient	(W/m^2K)
$MAPD$	mean absolute percentage deviation	(–)
$\dot{w}_{\mathrm{exp}}$	power output from the turbine	(kW)
$\dot{w}_{net}$	net power output	(kW)
$\dot{w}_p$	power consumption of the pump	(kW)
η_{gen}	the efficiency of the electric generator	(–)

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