PAPER ID: 1145
DOI: 10.18462/iir.rankine.2020.1145

Enabling Power Production from Challenging Industrial Off-Gas – Model-Based Investigation of a Novel Heat Recovery Concept

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ABSTRACT

Off-gas from the metal industry is a significant surplus heat source that is often not utilized due to lack of internal and external heat demands. Power production from the surplus heat in the off-gas could be a promising option for utilization. This work considers an off-gas at 150 °C from a metallurgical process, suitable for a Rankine Cycle (RC). Metallurgical off-gas typically contains particles that can deposit on heat exchanger surfaces, therefore requiring specialized heat recovery solutions for robustness and consistent performance. To maximize competitiveness of an RC implementation, it is crucial to recover the surplus heat at the highest possible temperature. We explore a novel plate-type heat exchanger concept for improved heat recovery from scaling-prone off-gas. Simulations show that the investigated concept can be competitive both in terms of weight and compactness compared to both a clean gas reference exchanger and alternative dirty gas concept.

Keywords: Heat exchanger modelling, challenging heat sources, heat recovery, compact heat exchangers.

1. INTRODUCTION

In order to meet the climate goals defined by the Paris Agreement of 2015, significant reductions in global greenhouse gas (GHG) emissions must be made in the coming decades. In its Sustainable Development Scenario, which is in line with international climate ambitions, IEA (2018) estimates that increased energy efficiency should cover approximately 40% of GHG emission reductions by 2040. A key contributor to higher energy efficiency will be increased utilisation of surplus heat. Today, large amounts of surplus heat are being wasted in the industry, especially at low to medium temperature levels. According to Papapetrou et al. (2018), around 100 TWh/year of surplus heat between 100-200 °C is available in the EU industry. A similar study by Bianchi et al. (2019) reported 174 TWh/year of surplus heat at 100-300 °C with a corresponding exergy of around 59 TWh/year.

An example of a significant surplus heat source at low to medium temperature is the off-gas from aluminium smelters, where the larger plants in Norway each reject around 1 TWh/y of heat through the off-gas. Due to a lack of internal and external heat demands, this heat is commonly not utilised. Power production could therefore be a promising option for increased energy efficiency. The off-gas temperature is typically around 150 °C close to the cell, and can likely be cooled to 80-90 °C without causing issues with acid dew points or downstream gas treatment. This temperature span is well suited for a Rankine Cycle. In order to achieve a high efficiency of the power cycle, it is critical to recover the heat at a sufficiently high temperature. This requires efficient heat exchange with small temperature differences, which is challenging to achieve for such heat sources. Particles and fines from the electrolysis are carried by the off-gas and can form solid layers on surfaces, which can lead to exchanger fouling (Clos et al., 2017). Thus, additional considerations must be taken in the heat exchanger design in order to ensure operational stability.

Different concepts for heat recovery from aluminium smelter off-gas are available in the literature. In Bouhabila et al. (2013) and de Gromard et al. (2014), a concept where off-gas flows across bundles of oval tubes equipped with rectangular fins is described. Pilot scale tests for approximately one year have been reported, but no recent references have been found on further testing of the concept. Verbraak et al. (2014) proposed a concept in which the off-gas flows along rows of cooled, vertical plates that are placed in series. The plates are retractable, and each row can be removed if maintenance or replacement is necessary. No experimental or simulation results were reported. A "tube-in-shell" type heat exchanger with off-gas flowing on the inside of straight tubes was considered by Sørhuus et al. (2010), Al Qassab et al. (2012) and Sørhuus et al. (2015). This technology has been in full-scale operation at several locations over many years, and is reported to have succeeded to resist major problems related to scale formation. It is indicated that scaling-related issues were avoided because of the core design in which off-gas flows undisturbed along straight channels.

Plate-fin heat exchangers are generally recognised as compact and efficient solutions for heat recovery in many applications. However, in the case of aluminium smelter off-gas, the introduction of surface enhancements is associated with an increased risk of scale formation. In this work we have explored new concepts with basis in plate-and-fin heat exchangers adapted such that the off-gas flows in straight channels without any enhancements, here referred to as a "plate-no-fin" concept. We hypothesise that such concepts have the potential to give increased heat exchanger performance for challenging off-gases. We will test our hypothesis through detailed heat exchanger modelling. Simulation results for the novel heat exchanger concept are compared to a cross-flow, finned-tube concept and a modified version without fins. The novel concept is therefore benchmarked both against a conventional clean gas exchanger and an alternative design adapted for particle-laden off-gas.

The main goal of this work is to provide an initial evaluation of the potential of the plate-no-fin heat exchanger concept. A series of assumptions are made regarding the operational and design limitations of the exchanger. The methodology of the work is described in section 2. In section 3, results are shown and discussed, and main conclusions are given in section 4.

2. METHODOLOGY

The heat exchanger models applied in this work have been implemented in an in-house modelling framework developed by SINTEF Energy Research, described in Skaugen et al. (2013). The framework can handle a multitude of geometries and relevant physical phenomena.

This section will give a description of the investigated cases and heat exchanger geometries, considerations made regarding scaling and erosion and the applied method for comparison of results.

2.1. Investigated cases and heat exchanger geometries

The reference case, representing off-gas conditions from a hypothetical aluminium smelter and the target heat exchanger performance, is described in Table 1. The target performance and parameters are identical for all simulations. Thermophysical properties of the off-gas is assumed to be air-equivalent. A maximum gas side pressure drop of 400 Pa is allowed.

Table 1: Description of reference case

Parameter	Value	Unit
Heat exchanger duty	2180	kW
Heat exchanger material	Steel	-
Material density	7500	$kg \times m^{-3}$
Off-gas composition	Air	-
Off-gas inlet temperature	150	°C
Off-gas inlet pressure	100	kPa
Off-gas outlet temperature	90	°C
Off-gas mass flow*	100	$kNm^3 \times h^{-1}$
Off-gas maximum pressure drop	400	Pa
Heat transfer fluid	Water	-
Heat transfer fluid inlet temperature	60	°C
Heat transfer fluid inlet pressure	5	bar
Heat transfer fluid outlet temperature	135	°C
Heat transfer fluid mass flow	6.9	$kg \times s^{-1}$

*Corresponds to 35.9 kg s^{-1}, equivalent to 10-20 electrolysis cells

In the left of Figure 1, an illustration of the finned-tube reference concept is shown. The gas flows across bundles of tubes with circular fins, and water flows inside the tubes. Two variations of plate-no-fin heat exchangers without surface enhancements on the gas side are considered. In both cases the off-gas flows in the open space between plates, and the cooling water flows counter-currently in channels inside the plates. However, in one of the cases, the depth is reduced linearly along the exchanger length. The off-gas is therefore gradually accelerated, which is expected to increase the heat transfer coefficient on the gas side at the expense of increased pressure drop. The two alternatives are illustrated in the middle and right of Figure 1. In the following, FT refers to the finned-tube reference concept, PNF the plate type exchanger with constant geometry, V-PNF the plate type exchanger with variable geometry and TNF a cross-flow tube heat exchanger without fins.

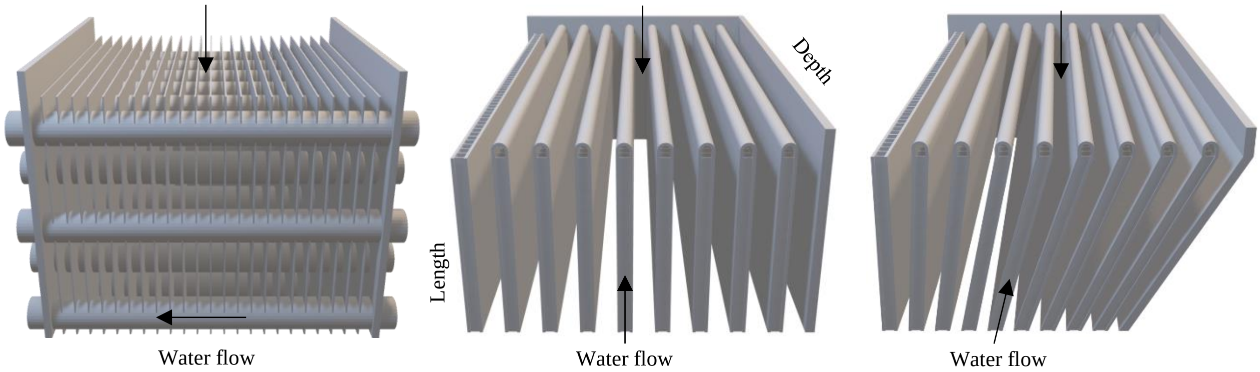

Figure 1: Illustrations of considered heat exchanger concepts. Left: finned-tube heat exchanger (FT). Middle: plate type heat exchanger with constant geometry (PNF). Right: plate type heat exchanger with variable geometry (V-PNF).

For each heat exchanger type, the conditions for both fluids were set equal to the reference case, as described in Table 1. Thus, the duty of each exchanger was identical. However, this can be achieved through several combinations of the geometrical design parameters, giving large variations in weight, footprint and volume. Therefore, a parametric analysis to identify the most promising design for each case was performed. No mathematical optimisation was carried out for the plate-type exchangers, instead specific combinations fulfilling the target duty and other requirements were extracted from the parameter study results. In this modelling-based approach, it is not possible to clearly conclude on the minimum possible diameters or channel gaps, and a range has therefore been considered. Table 2 provides an overview of the values of fixed and varied design parameters in this study. In Figure 2, an explanation of the parameters governing plate design for the working fluid is provided.

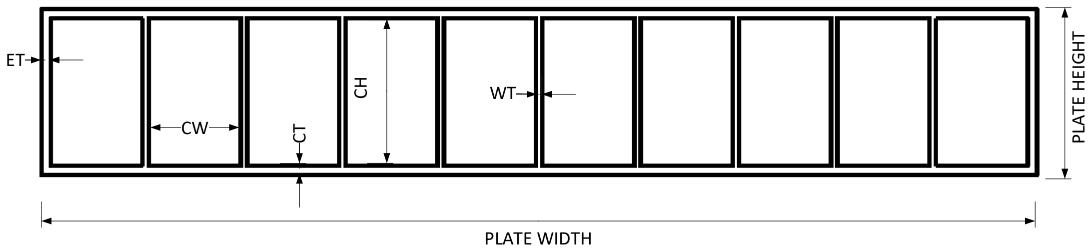

Figure 2: Explanation of plate design parameters for working fluid: channel width (CW), channel height (CH), wall thickness (CT), web thickness (WT) and end thickness (ET).

2.2. Scaling and erosion considerations

As previously mentioned, the particles and fines carried by the off-gas can lead to scale formation. Additionally, alumina particles are abrasive, which can lead to erosion of the heat exchanger surfaces at certain operating conditions. In order to achieve stable long-term operation, it is expected that a balance between scale formation and removal due to erosion must be established. Scale formation will dominate at low gas velocities, and erosion will be prominent at high velocities. An upper gas velocity limit of 20 $m \times s^{-1}$ was applied in this work. For the variable geometry concept V-PNF, the degree of contraction is effectively limited by this velocity constraint.

The gas velocity at the heat exchanger inlet is also of critical importance. At this location, a fraction of the off-gas impacts perpendicularly on the heat exchanger surface and the risk of scale formation is high. In this work, the gas side inlet velocity is limited to 12 m×s^{-1} for the plate-type concepts.

Table 2: The values of fixed and varied geometrical design parameters used in heat exchanger simulations

Fixed parameters	Unit	FT	PNF	V-PNF	TNF
Channel height	mm	-	6.00	6.00	-
Channel width	mm	-	5.00	5.00	-
Wall thickness	mm	2.00	1.00	1.00	2.00
Web thickness	mm	-	0.85	0.85	-
End thickness	mm	-	1.05	1.05	-
Shell thickness	mm	8.00	8.00	8.00	8.00
Fin type	-	Round, Plain	-	-	-
Fin thickness	mm	0.80	-	-	-
Inlet diffusor angle	degrees	30	30	30	30
Outlet diffusor angle	degrees	45	45	45	45
Varied parameters					
Gas side hydraulic diameter*	mm	26-49	10-50	10-50	24-54
Number of tubes or plates	-	483-1032	88-228	88-228	1908-4968
Heat exchanger core width	m	3.7-4.7	3.0	3.0	4.3-5.3
Heat exchanger core depth	m	0.8-1.5	1.6-3.1	1.6-3.1	2.3-2.6
Heat exchanger core length	m	2.4-2.8	1.4-9.6	1.1-7.4	3.8-3.9
Linear contraction angle	degrees	-	-	2.9-35	-
Transversal pitch/tube diameter	ratio	-	-	-	1.15-4.0
Longitudinal pitch/tube diameter	ratio	-	-	-	1.15-4.0
Fin height	mm	9.53-13.9	-	-	-
Fin pitch	mm	4.75-5.76	-	-	-

* Hydraulic diameter is equal to outer tube diameter for FT and TNF, and two times the plate gap for PNF and V-PNF

2.3. Heat transfer coefficient and pressure drop correlations

An overview of the applied correlations for gas and water heat transfer coefficients and pressure drop for the various heat exchanger concepts is provided in Table 3.

Table 3: Correlations for gas and water heat transfer coefficients applied in heat exchanger modelling.

Heat exchanger concept	Gas heat transfer coeff.	Water heat transfer coeff.	Gas pressure drop	Water pressure drop
Finned tube (FT)	ESCOA (2003)	Gnielinski (1975)	ESCOA (2003)	Selander (1978)
Plate-no-fin (PNF)	Gnielinski (1975)	Gnielinski (1975)	Selander (1978)	Selander (1978)
Variable plate-no-fin (V-PNF)	Gnielinski (1975)	Gnielinski (1975)	Selander (1978)	Selander (1978)
Tube-no-fin (TNF)	ESDU (1973)	Gnielinski (1975)	HEDH (1998)	Selander (1978)

2.4. Comparison of results

The main goal of this work has been to provide an initial evaluation of the potential of the modified plate type heat exchanger concept. Therefore, emphasis has been on the heat exchanger core, i.e. the part containing heat transfer surfaces. As a result, some elements that would be necessary in a real-life heat recovery system are omitted in our assessment. The analysis includes inlet and outlet diffusors and ducting, but omits for example structural elements and supports.

The target heat exchanger duty is equal for all cases considered in this work, and we have chosen to compare concepts based on the following properties of the heat exchangers: 1) weight, 2) footprint, 3) volume and 4) gas side pressure drop.

3. RESULTS AND DISCUSSION

A typical result from the parametric analysis is shown in Figure 3, where iso-curves for the PNF concept are shown for an exhaust gap and channel height of 6 mm. In this case, the length and width of the exchanger was varied. Similar contour plots can be made for the other concepts through systematic variations of two of the design parameters, while keeping all other parameters constant. It is evident from the figure that several combinations of heat exchanger width and length give the same duty, gas-side pressure drop and core weight. However, only one combination gives the required duty of 2180 kW while simultaneously meeting the pressure drop requirement of 400 Pa, indicated by a cross in the figure.

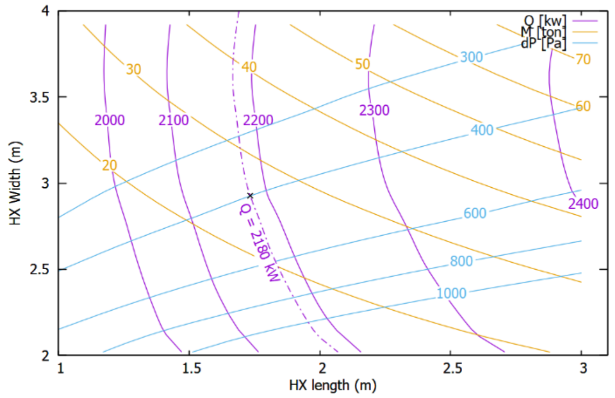

Figure 3: Contour plot for the PNF concept for an exhaust gap and channel height of 6 mm. Iso-curves for heat exchanger duty (purple), gas-side pressure drop (blue) and heat exchanger core weight (yellow) as a function of width and length.

In Figure 4 (left), total heat exchanger weights are compared for a wide range of hydraulic diameters. In all cases, reducing the hydraulic diameter gives a lower weight. The PNF and TNF concepts have similar total weights, ranging from around 25 to 35 tons. It is evident from the figure that the introduction of variable geometry gives a significant weight reduction. The total weight of the V-PNF varies from 15 to around 22 tons, and is lower than the clean gas FT concept for hydraulic diameters above 35 mm.

The total heat exchanger volume for the different concepts is shown in Figure 4 (right). Inlet and outlet ducts are included. The figure shows that although they are comparable in weight, the plate-type concepts are less voluminous than the tube-based concepts. The TNF requires significantly more volume than the other concepts, and both PNF and V-PNF are more compact than the FT concept.

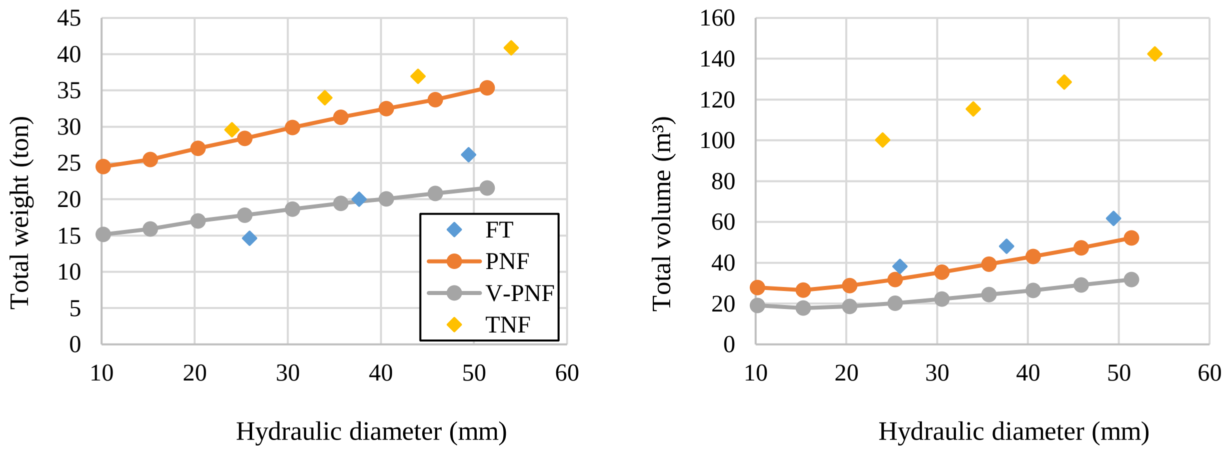

Figure 4: Heat exchanger total weight (left) and volume (right) vs. hydraulic diameter.

The above analysis shows that choosing the smallest possible hydraulic diameter will be beneficial for heat exchanger weight. However, in practice there will be a lower limit for plate gap, and demonstration of concepts in an actual plant environment will be necessary. In this work, we have chosen to compare the concepts for hydraulic diameters around 20 mm. In Table 4, a summary of the chosen heat exchanger design parameters is given and the main results are compared.

It can be seen that the number of plates is equal for PNF and V-PNF. They have identical inlet dimensions, and since the contraction only occurs in the depth dimension, the number of plates is unaffected by the introduction of variable geometry. The exchanger width and plate gap remains constant throughout the V-PNF exchanger. The number of tubes in FT and TNF is significantly higher than the number of plates for the other exchangers. The degree of contraction for V-PNF was 12.3, which gave an outlet velocity of 19.9 m×s^{-1}, very close to the chosen upper limit.

Table 4: Summary of chosen heat exchanger design parameters and main results

Parameter	Unit	FT	PNF	V-PNF	TNF
Hydraulic diameter	mm	25.9	20.0	20.0	24
Number of tubes/plates	-	1032	164	164	4968
Heat exchanger width	m	3.72	3.00	3.00	4.38
Heat exchanger depth	m	0.82	2.16	2.16	1.13
Heat exchanger total length	m	4.93	5.08	4.12	7.19
Linear contraction angle	degrees	-	-	12.3	-
Transversal pitch/tube diameter	ratio	-	-	-	1.6
Longitudinal pitch/tube diameter	ratio	-	-	-	1.2
Fin height	mm	9.53	-	-	-
Fin pitch	mm	5.76	-	-	-
Main result					
Heat exchanger total weight	tons	14.6	27.0	17.0	29.6
Heat exchanger total footprint	m^2	12.5	6.48	6.48	21.6
Heat exchanger total volume	m^3	38.2	28.9	18.6	155.4
Heat exchanger area – Gas side	m^2	1757	2336	1319	1649
Heat exchanger area – Water side	m^2	241	4179	2806	1374
Gas side pressure drop	Pa	400	281	374	400
Gas side inlet velocity	m×s^{-1}	7.6	12.0	12.0	6.6
Gas side outlet velocity	m×s^{-1}	6.5	10.3	19.9	5.6
Avg. heat transfer coeff. (gas/water)	W×m^{-2}×K^{-1}	64/4466	47/535	61/673	75/2070
Avg. U-value (related to gas side area)	W×m^{-2}×K^{-1}	57.3	45	58	61.3

As seen from the main results, the two investigated plate-type concepts vary significantly in weight. The weight of the straight PNF concept was 27.0 tons, which is similar to the TNF concept. However, the V-PNF variable geometry plate-type exchanger has a weight of 17.0 tons, which is 37% lower than the PNF exchanger and only 16.4% heavier than the clean gas FT exchanger. Another advantage of the plate-type concepts is their compactness, which could be an enabler for implementation in space-limited industrial plants. The V-PNF concept has a total volume of 18.6 m^3, which is around 51% less than the FT exchanger. Notice also that the gas side pressure drop of the PNF concept is lower than the limit of 400 Pa.

In order to further explain the difference in performance between the concepts, it is necessary to investigate how various properties vary along the length of the heat exchangers. In Figure 5, the accumulated pressure drop, gas velocity, gas side heat transfer coefficient and pressure gradient is shown as a function of dimensionless heat exchanger length for the hydraulic diameters shown in Table 4.

The effect of variable geometry is clearly seen in the velocity profile in Figure 5. The PNF and V-PNF concepts have the same inlet velocity, but the gradual contraction leads to a significant increase in velocity for V-PNF. The trend in gas-side pressure gradient follows the velocity profile. For approximately 60% of the exchanger length, the TNF exchanger has a larger pressure gradient than the V-PNF concept, before the velocity increase leads to a larger gradient. Due to the presence of fins on the gas side, the pressure gradient is largest for the FT exchanger. Although V-PNF has a significantly higher pressure drop gradient at the end of the exchanger, it has a lower overall pressure drop than the tube concepts. This is caused by the difference in heat exchanger length. To further improve the variable geometry concept, a non-linear variable geometry could be considered, where the gas is accelerated quickly to a high velocity in the first part of the exchanger. A small contraction angle could be used in the remaining part of the unit to counteract frictional losses, which in practice would give an almost constant velocity throughout the exchanger.

It can be seen from the gas-side heat transfer coefficient profiles that inlet effects are considered only in the correlations used for the plate-type heat exchangers. The heat transfer coefficient decreases significantly within the first few percent of the length. This effect constitutes an increase in the overall U-value of less than 5%.

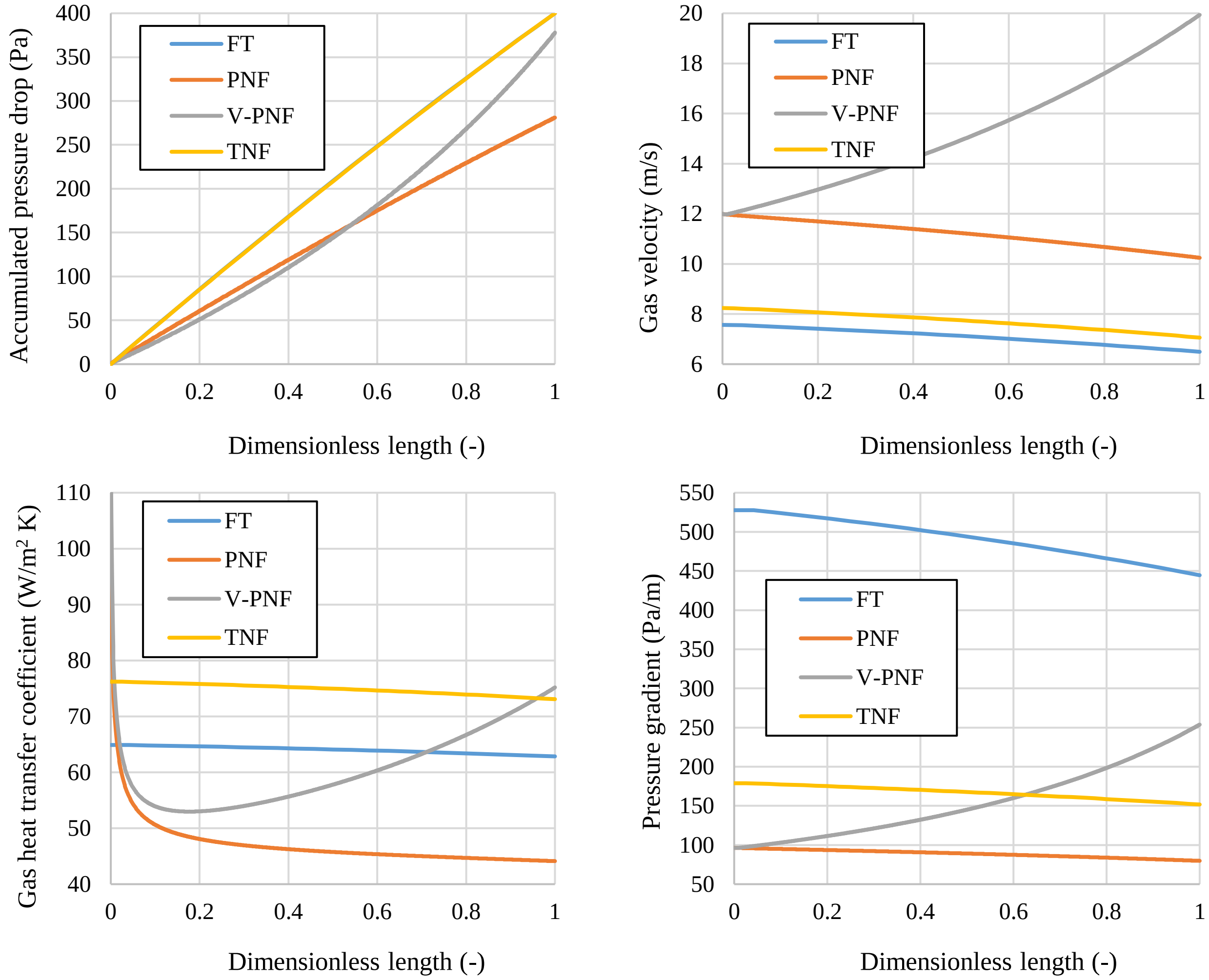

Figure 5: Accumulated pressure drop, gas velocity, gas heat transfer coefficient and pressure gradient vs. dimensionless length for hydraulic diameters around 20 mm.

4. CONCLUSIONS

In this work, a modified plate-and-fin type heat exchanger without surface enhancements on the gas side has been investigated for heat recovery from scaling-prone off-gas. Two variations of the plate-no-fin heat exchanger were studied: a straight concept and a concept with a gradual depth reduction along the heat exchanger length. The main goal of the work was to provide an initial evaluation of the potential of such concepts. Results were compared to both a finned-tube clean gas exchanger and a modified version without fins. Simulations using detailed heat exchanger models implemented in an in-house modelling framework were used to compare concepts. The concepts considered in this work have not yet been validated experimentally, and in the future it will be necessary to test the plate-no-fin heat exchangers in-situ on real aluminium electrolysis off-gas.

The simulations show that plate-type heat exchangers can be a promising alternative for aluminium smelter off-gas. The variable geometry plate-type exchanger showed a 37% weight reduction compared to the straight plate-type concept, demonstrating that the introduction of variable geometry can give significant improvements. The V-PNF exchanger was only 16.4% heavier than the finned-tube reference exchanger. The plate-type concepts had lower footprints and volumes than the reference cases. The V-PNF concept had a 51%

smaller volume than the finned-tube exchanger. The compactness of the plate-type concepts could be an enabler for industrial implementation.

However, it should be emphasised that this work is only a first-time evaluation of the plate-type concepts. Focus has been on the heat exchanger core, i.e. the part containing heat transfer surfaces, and structural elements and supports were omitted from the evaluation. The effect of such elements on the total weight and pressure drop should be investigated in the future. Additionally, alternatives to the single element linear contraction from this study should be investigated, to fully exploit the potential of variable geometry.

ACKNOWLEDGEMENTS

This publication has been funded by HighEFF - Centre for an Energy Efficient and Competitive Industry for the Future, an 8-year Research Centre under the FME-scheme (Centre for Environment-friendly Energy Research, 257632/E20). The authors gratefully acknowledge the financial support from the Research Council of Norway and user partners of HighEFF.

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