NEW CONCEPTS FOR R245FA DIRECT ORC APPLICATION IN HIGH TEMPERATURE PROCESS HEAT SYSTEMS

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ABSTRACT

The application of non-flammable refrigerants (R245fa) for direct heat extraction from high temperature heat source (above 380°C) is normally limited due to the risk of refrigerant decomposition, where a decomposition threshold of 250°C was reported. The option is to incorporate indirect heat extraction loop using heat transfer fluid. This option is associated with an additional cost and complications compared to that encountered in direct heat extraction. In this paper, two new concepts were proposed for direct heat extraction. The concepts were studied analytically and computationally. A reference design of highly finned tube evaporator was used in both options. In the first, a harvested high temperature gas (up to 470°C) was mixed with different portions of intake air to provide adequate temperature control of the gas inlet temperature. Three analytical studies were developed and several CFD models were generated. More than twenty different operating conditions were assessed. With this concept the significant fluctuations in the harvested gas temperatures was mitigated and the workable zone was determined. No considerable increase was found in the resulting pressure drop. However, overall performance showed slight decrease in thermal duty compared to that obtained with high intensity temperatures of the harvested gas. Applying this eliminates the risk of the refrigerant reaching localized decomposition temperature. In the second concept, open pore metal foam was implemented inside the tubes at effective locations where high risk of refrigerant decomposition could occur. Evaporator performance associated with the harvested gas was compared. Significant improvement in thermal performance was achieved resulting in considerable reduction in the size of the heat exchanger and elimination of hot zones associated with refrigerant decomposition. The penalty was a significant increase in pressure drop, which strongly increased with an increase in mass velocity. Implementing porous media at effective locations is the key parameter in this novel concept where the pressure drop was controlled under acceptable level.

1. BACKGROUND

1.1 Literature Review

The refrigerant R245fa is commonly used in the Organic Rankine Cycle (ORC) as a non-flammable fluid for power generation applications in direct heat extraction for a variety of waste heat sources. For low temperature geothermal sources up to about 120 °C, R134a is commonly used at high pressure (up to 45 bar) in real applications, whereas for medium temperature geothermal sources up to about 200 °C R245fa is used at lower pressure as a preferred working fluid, as reviewed by Invernizzi et al. (2016). This 200°C falls in the category specified by Vetter et al. (2013), where optimum ORC power output could be obtained if the working fluid have a critical temperature (R245fa critical temperature 154.16°C) of 0.8 times the heat source temperature.

Also, the critical temperature (154.16°C) of R245fa contributed to R245fa applications over a wide heat source temperature ranges because it shows little decrease in ORC thermal efficiency, as indicated by Xu and Yu (2014). In the same manner, Schroeder and Leslie (2010) indicated that for nearly ideal working fluids used in ORC engine, R245fa and pentane are used for lower temperature sources and toluene (flammable fluid) is used for higher temperature sources. Li and Wang (2016) simulated ORC performance with different working fluids for a range of exhaust gas heat source inlet temperatures (200 – 700°C). The authors reported that R245fa is one of the optimum fluids for exhaust gas temperature up to 300°C, while, flammable fluids were selected for higher exhaust gas temperature.

More R245fa applciations at high temperature gas heat source ORC applications was performed by Pavel and Mohamad (2004). The authores examined the performance of R245fa compared to water, and R123 in a combined power cycle and heat exchanger. However, the pilot scale experimental results were based on gas source temperature of 200°C. High potential for much higher temperatures in process heat recovery system is found in future alternatives for H_2 production from geothermal (superheated steam at 230°C 15 bar) assisted high temperature steam electrolysis process. In such process, high temperature (300°C or so) exhaust gas is produced, and a potential for ORC heat recovery is required, as assessed by Kanoglu et al. (2011).

All the above refers to the preferred application of the refrigerant R245fa as a non-flammable fluid compared to other refrigerants, as long as its temperature is controlled below the critical level. By adjusting the pressure and temperature at the evaporator according to the turbine requirements, the physical properties of the working fluid could be tuned and ORC efficiency could be enhanced, as designated by Radulovic and Beleno Castaneda (2014). In this paper, the feasibility of applying the refrigerant R245fa at high temperature gas heat source in ORC highly finned tube evaporator was examined. Heat transfer performance was compared between a reference design and that obtained using innovative concepts. This work is part of Above Ground Geothermal & Allied Technologies (AGGAT), which is a HERA led co-operative research platform to support the development of ORC plant manufactured for the low enthalpy, geothermal and waste heat market.

1.2 Fluids Degradations and Impacts at High Temperature Application

In terms of degradation, from decomposition analysis for a number of pure hydrocarbons, Mao et al. (2014) showed that all organic materials undergo degradation and cracking as temperature increases. However, the degree of degradation is accelerated by the presence of air due to oxidation. Yet, smaller molecular weight organic molecules are more resistant to thermal cracking compared to that with large molecular weight organic. Whereas, ring structure hydrocarbons, such as toluene, behave more like lower molecular weight fluids, in terms of tolerance to degradation.

The high critical temperature criteria makes toluene potentially a more efficient working fluid compared to pentane or R245fa for higher temperature heat sources. However, to comply with safety regulations, the flammable characteristic of toluene and the high pressure application make the cost of the heat exchanger much higher than that required for R245fa. In the same manner Panesar (2013) compared the performance of R245fa with acetone for high temperature heat source (about 400°C). The high pressure requirements (up to 40 bar) for high ORC efficiency obtained with acetone also attribute to considerable increase (up to 12%) in the heat exchanger cost, as reported by Invernizzi, Iora et al. 2016.

The field of investigating high efficiency fluids for high temperature gas applications is in continuous progress. Recently, Panesar (2016) proposed an innovative ORC approach for high temperature gas (400°C) applications, where novel organic blends with toluene (80%) and hexamethyldisiloxane have been formulated to retain higher thermal stability, high molecular weight, low environmental impact and efficient use in heat exchangers. The author reported that the advantage of 15–18% lower $/kW value was presented compared to that obtained using the pure fluid, thus improving marketing potential. In conclusions, it can be realized that research is still required to identify suitable working fluids to tolerate high temperatures applications.

1.3 R245fa Degradation and Limitations in Industrial High Temperature Application

Industrial application of the refrigerant R245fa is limited at high temperature gas heat source (above 380°C) due to the risk of refrigerant decomposition. A decomposition threshold of 250°C has been reported by Honeywell (2001), claiming that decomposition products such as Hydrofluoric Acid (HF) and carbonyl halides could be formed. This was further investigated by Angelino and Invernizzi (2003), who performed experimental stability tests on several Ozone depleting refrigerants (ODR), including R245fa. No sign of decomposition was observed when the refrigerant was heated to temperatures of 150, 250, and 300°C for 100 h. Chemical analysis confirmed that the fluid can be considered stable at temperatures up to 300°C. While, at 330 °C, after a fixed reading of 58 bar for 31 h, a major sign of decomposition was indicated.

In cyclic systems such as ORC the working medium is briefly exposed to high temperatures so fluid degradation should be limited. Apart from that, the main concern is refrigerant overheating to levels considerably above the supercritical level (36.51 bar, 154.16°C) where refrigerant condensation could no longer be distinguished and the basic ORC evaporation-condensation cycle could no longer be applied.

1.4 Objectives

The objectives of this study were:

- To determine safe operating zone for R245fa.
- To assess feasibility of extending the workable zone with new concepts.
- To examine the impact of the new concept on the overall performance of the evaporator compared to that obtained using the reference design.

2. INNOVATIVE CONCEPTS FOR R245FA EXTENDED TEMPERATURE APPLICATIONS

Taking into account the critical challenges in R245fa applications at high temperature heat source (above 200°C), it was highly essential to investigate the performance with a new concept. Not to allow safe and economic application only, but also to further extend the acceptable temperature range and improve thermal performance.

2.1 Intake Air Concept

This concept is simply based on reducing the temperature of the harvested gas by mixing the gas with controlled fractions of intake air. By this concept, the possible daily and seasonal fluctuations in the temperature of the harvested gas are effectively mitigated and the temperature is controlled to that required by the evaporator and the turbine in the ORC engine.

2.2 Porous Media Concept

During the course of our heat augmentation studies, it was found that the risk of R245fa overheating was disappeared when porous media was implemented at effective locations. Such extremely important outcome was utilized as a basis for this novel concept.

2.2.1 Augmentation of Heat Transfer with Porous Media

In terms of heat transfer augmentation, open literature (Gholamreza et al., 2016a; Gholamreza et al., 2016b) indicated that by inserting open pore copper foams (Table 1) inside mini tubes (4 mm internal diameter) heat transfer coefficient increased by about three fold compared to empty tubes. With the variation in thermal performance between different pores per inch (PPI) densities (20 and 30 PPI) have diminished when operating at higher fluxes of mass (700 kg/m^2s compared to 400 kg/m^2s) and heat (40 kW/m^2 compared to 20 kW/m^2). Whereas, pressure drop showed strong dependency on mass flux (35% increase at the higher mass flux), and vapour quality (5 folds increase with an increase in vapour quality from 0.1 to 0.7). In terms of pressure drop (ΔP), another study (Boomsma and Poulikakos, 2002) indicated that the pressure drop across different metal foams (10 – 40 PPI) of a specified length (L) becomes a quadratic function of flow velocity (v) once the velocity level exceeds 0.1 m/s. Above such level, pressure drop deviates from the linear Darcy regime, and the inertia coefficient (C) become a key parameter influencing the pressure drop, as defined in equation 1. For accurate prediction of pressure drop, experimental examination was vital to determine the inertia coefficient, which depends on the pores hydraulic diameter (D_p), foam structure, and porosity (ϵ). However, it can be calculated based on Ergun (1952) equation (2) for flow through packed column, which is a form of equation 1:

$$\frac{\Delta P}{L} = \frac{\mu}{K} v + \rho C v^2 \qquad \text{Equation 1}$$

$$\frac{\Delta P}{L} = \frac{150(1-\varepsilon)^2}{D_p^2 \varepsilon^3} \mu v + \frac{1.75(1-\varepsilon)}{D_p \varepsilon^3} \rho v^2 \qquad \text{Equation 2}$$

Whereas μ, and ρ are processing fluid viscosity (Pa.s), and density (kg/m^3), repevtively. and $K = \frac{D_p^2 \varepsilon^3}{150(1-\varepsilon)^2}$ is permeability (m^2), $C = \frac{1.75(1-\varepsilon)}{D_p \varepsilon^3}$ (m^{-1}), and D_p is pores opening diameter (m).

This implies that determining an effective location for implementing the porous media, along with the pores density selection are key parameters in this novel concept. Based on the operating conditions and the findings reported above, 20 PPI foam (see Table 1) was selected for the purpose of this study.

Table 1: Parameters of the open pores foams (Gholamreza et al., 2016a; Gholamreza et al., 2016b).

Pores density (PPI)	Porosity (ϵ)	Surface area to volume ratio (m^2/m^3)	Permeability (m^2)	Tube inner diameter (m)
20	0.9	2310	1.99 E-8	0.004
30	0.9	3520	9.41 E-9	0.004

3. THERMAL ANALYSIS APPROACH

Two approaches were followed, for thermal analysis, analytical approach and computational fluid dynamic (CFD) approach. Details descriptions of the two approaches have been discussed in our previous paper (Abbas et al., 2015).

3.1 Performance Prediction using Analytical Study

The performance of a reference design of highly finned tube evaporator shown in Figure 1, was predicted analytically. The analytical method was performed in Excel based on the number of transfer unit (NTU) approach applied on pass by pass method. A selection of reported empirical correlations equivalent to flow conditions of each stream in the evaporator were employed. Single phase flow correlation for turbulent flow around a bundle of tubes was used at the gas side, and two phase flow for boiling was used at the tube side (Abbas et al., 2015).

In this approach, refrigerant average skin temperature ($T_{avg\text{-}skin\text{-}ref}$) was calculated based on the arithmetic average between the refrigerant inlet temperature ($T_{ref\text{-}in}$) and the refrigerant outlet temperature ($T_{ref\text{-}out}$) and thermal duty (Q) divided by internal surface area (A_i) and internal heat transfer coefficient (h_i) at each pass of the evaporator, as defined in equation 3:

$$T_{avg-skin-ref} = \left(\frac{T_{ref-in} + T_{ref-out}}{2} \right) + \frac{Q}{A_i h_i} \qquad \text{Equation 3}$$

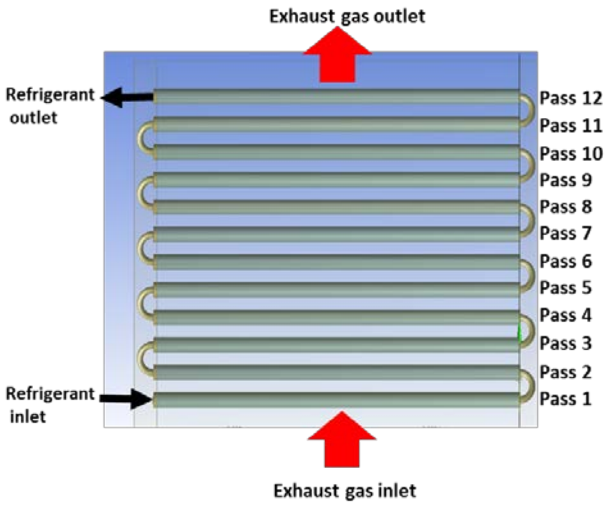


Figure 1: Schematic representation of a reference design highly finned tube evaporator.

3.2 Performance Prediction using Computational Study

A Computational Fluid Dynamic (CFD) model of highly finned tube (Figure 2) was developed replicating conditions at the major affected pass by the high temperature heat source in a reference design evaporator. The model was developed using the advance modelling package ANSYS/Workbench/CFX. The working fluid (inside the tubes) was R245fa. The gas was modelled as an ideal gas.

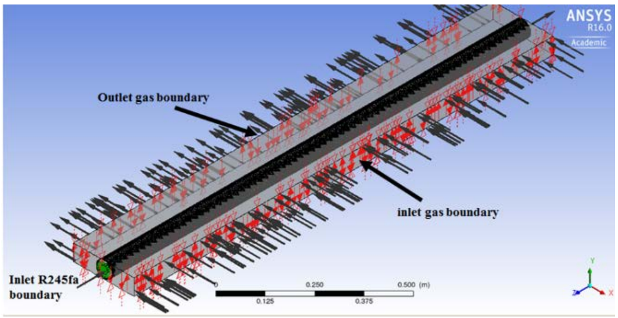


Figure 2: CFD model replicating conditions at the major affected pass in highly finned tube evaporator.

3.2.1 Resources for CFD Analysis

CFD analysis was performed by means of ANSYS/CFX. High performance computing (HPC) system of NESI cluster located at the University of Auckland was employed to run the simulations. The cluster was accessed via VPN remote connection authorised by The University of Auckland. Parallel licence of ANSYS solver was employed in the solution. The consumed computational time was up to 3 hrs if 200 iterations were specified for solution. This is normally considered a reasonable range if the size of the generated mesh was taken into account (2,813,905 nodes and 7,522,026 elements forming mesh of 514 MB). With this privilege, the ability to examine new concepts in a cost effective method was achieved.

4. RESULTS

4.1 Workable Zone with the Reference Case

Average skin temperature results at each pass of the evaporator obtained using the analytical study for a range of harvested gas inlet temperatures are shown in Figure 3. The major affected passes are those located at the first row of tubes encountered with the high temperature gas. To assess this further, average skin temperature results at the major affected pass were compared with maximum skin temperature results (localized hot zones) obtained using the CFD study. The comparison is shown in Figure 4, and the resulting duty at each condition is shown in Table 2. Temperature increase in both studies (average and maximum) showed similar trend. However, the difference between the two studies increased with the increase in the gas temperature. This was attributed to the considerable increase in the local hot zone temperatures formed at the refrigerant R245fa side. This was effectively captured by the CFD study, as presented in Figure 5. A workable zone was determined associated with gas inlet temperature between 390°C and 400°C. The temperature of the bulk refrigerant was maintained at saturation, as shown in Figure 6.

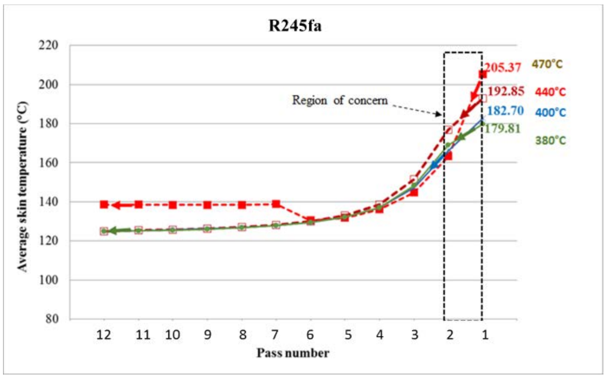


Figure 3 : Average skin temperatures at the twelve passes of the evaporator obtained using the analytical study.

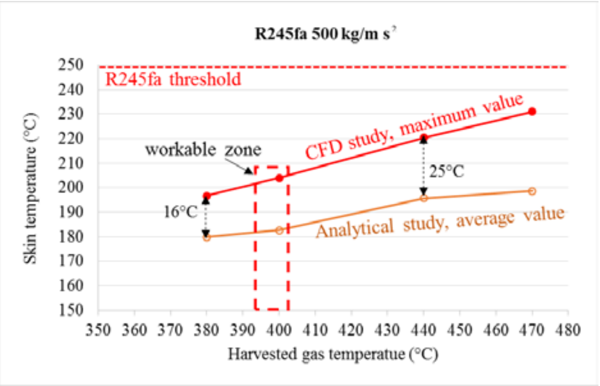


Figure 4 : Skin temperature results obtained using CFD (ANSYS/CFX) and the analytical study with different gas inlet temperatures.

Table 2 : Temperatures and duty results obtained using ANSYS/CFX for the reference case.

$T_{in\text{-}gas}$ (°C)	$T_{in\text{-}ref}$ (°C)	$T_{skin\text{-}max}$ (°C)	Duty (kW)	$T_{ref\text{-}out}$ (°C)
470	80	231.0	10.07	118.32
440	80	220.3	9.88	115.89
410	80	208.6	9.04	113.23
400*	80	204.0	8.76	112.32
380	80	196.6	8.20	110.43

* Selected Safe operation point.

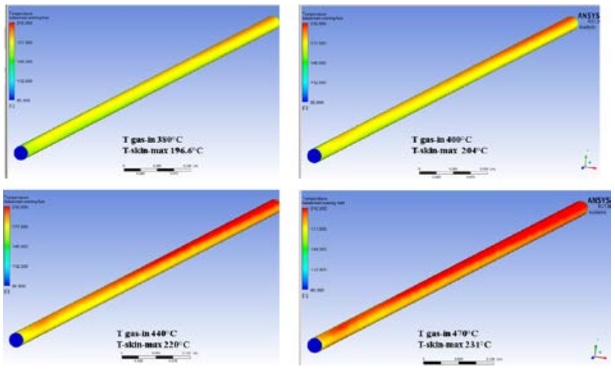


Figure 5 : Skin temperature contours at the selected pass in the evaporator.

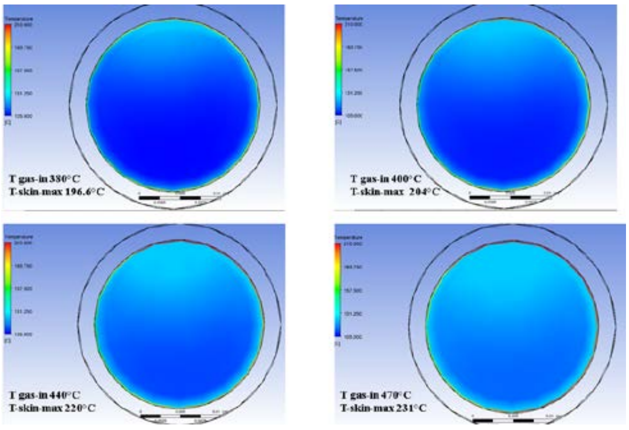


Figure 6 : Temperature contours of R245fa in cross-sectional view at the outlet boundary of the major affected pass, obtained using ANSYS/CFX for a range of gas inlet temperatures.

4.2 Results with Intake Air Concept

Temperature results obtained using CFD associated with mixed fractions of intake 15°C air are shown in Figure 7. The resulting temperatures of the mixed stream, skin temperate, and the outlet temperature of the refrigerant were all decreased with the introduced increase in the mass fraction of the intake air. Since duty output was also decreased (see Table 3), a practical working area of 0.188 fraction of intake air was proposed. Temperature contours of the resulting mixed stream with the proposed fraction is shown in Figure 8, where the high inlet temperature (470°C) of the harvested gas was effectively decreased to about 385°C. At this level, the associated skin temperature range (206 - 208°C maximum) presented no risk of R245fa overheating or decomposition.

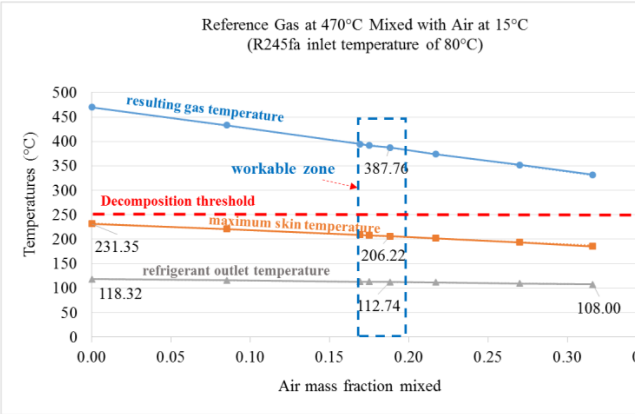


Figure 7: Workable zone with intake air concept, obtained using ANSYS/CFX.

Table 3: Evaporator performance with input fractions of intake air mixed with gas at maximum temperature level (470°C) obtained using ANSYS/CFX.

Intake air fraction	$T_{mix\text{-}gas}$ (°C)	$T_{skin\text{-}max}$ (°C)	Duty (kW)	$T_{ref\text{-}out}$ (°C)
0.08	433.00	220.70	9.92	116.00
0.18	394.60	208.95	9.08	113.00
0.18	391.80	208.00	9.01	113.00
0.19	387.76	206.22	8.88	112.74
0.22	374.00	201.80	8.58	111.72
0.27	352.00	193.46	8.01	109.80
0.31	332.00	185.50	7.51	108.00

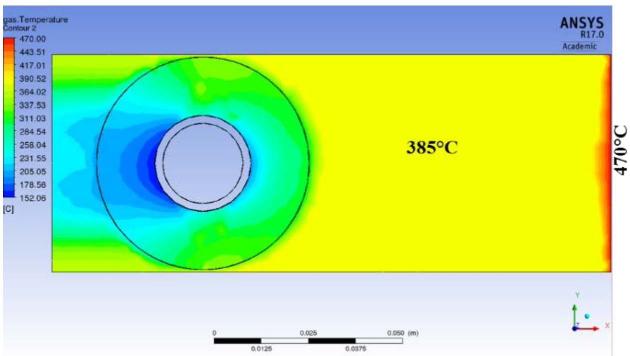


Figure 8: Temperature contour resulted with the proposed intake air (15°C).

4.2.1 Impact of Refrigerant Inlet Temperature

Using the case with the proposed fraction of intake air (see section 4.2), the impact of different inlet temperatures of the refrigerant R245fa was assessed computationally. The assessment was based on R245fa maximum skin temperature and outlet temperature at main influenced pass. The results (Figure 9) showed that maximum skin temperature increased with the increase in the inlet temperature from 63 up to about 90°C. Above that, the increase in temperatures was not significant. This was attributed to the increase in the refrigerant temperature to constant saturation level (124.38°C), and the additional heat was consumed in the evaporation process. To demonstrate this, contours of skin temperature (Figure 10), and vapour quality (Figure 11) were presented.

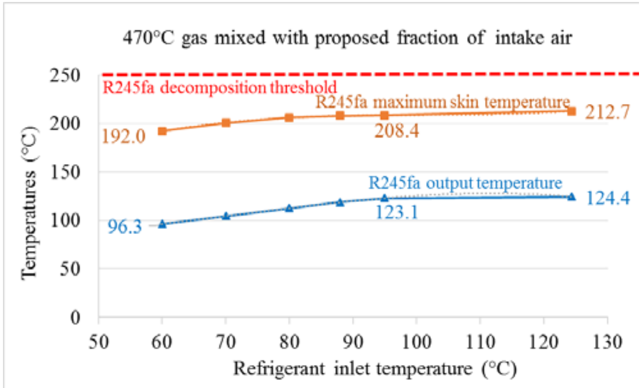


Figure 9: Maximum skin temperature and refrigerant R245fa outlet temperature at the selected pass of the evaporator for different refrigerant inlet temperatures obtained using ANSYS/CFX.

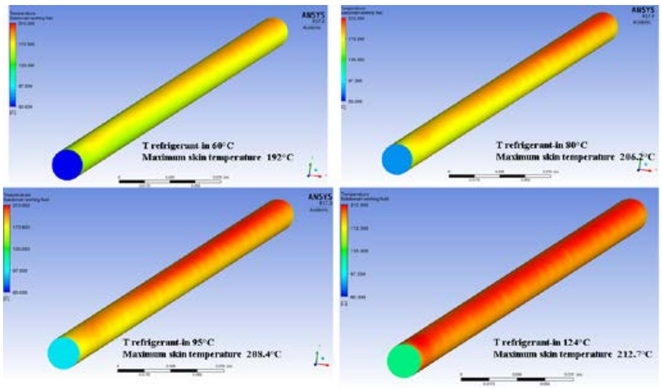


Figure 10: Temperature contours at R245fa side for different inlet temperatures associated with the proposed intake air.

Evaporator overall performance at maximum and lower temperature intensities was compared with that obtained using the proposed mixed fraction, as listed in Table 4. From the comparison, it was found that overall duty was decreased by 7%, but the temperature of hot skin zones was reduced by 11%. Therefore, the risk of R245fa overheating was avoided. However, when compared with lower temperature intensity (380°C), overall duty was increased considerably (by 22%) and full evaporation was achieved in contrast to the reference case.

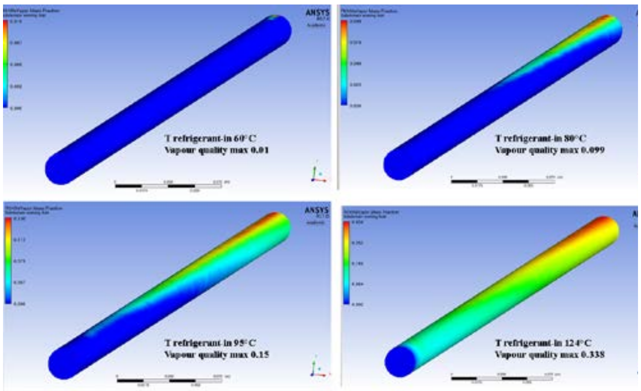


Figure 11 : Vapour quality contours associated with the high temperature zones with proposed fraction of 15°C intake air for a range of R245fa inlet temperatures.

Table 4 : Evaporator overall performance for the reference cases compared with resulting performance after mixing with proposed fraction of intake 15°C air.

Parameters	Reference case	Reference case	Intake air
gas (mixed stream) inlet temperature (°C)	470.00	380.00	380.00
Thermal duty (kW)	36.50	27.79	33.86
Maximum skin temperature (°C)	231.00 (risk)*	197.00 (no risk)	206.00 (no risk)
dP shell (kPa)	0.11	0.13	0.14
dP tubes (kPa)	17.00	9.04	14.38
average Fin efficiency	0.60	0.58	0.57
vapour quality (x)	1.00	0.78	1.00

*Risk of R245fa overheating

4.3 Results with Porous Media Concept

Skin temperature (Figure 12) at the major affected pass facing high temperature intensity (470°C) gas resulted with a maximum of 135°C. Hence, risk of R245fa decomposition or overheating was avoided, and no constraint was imposed on the workable zone. Also, thermal duty (Figure 13) at the selected pass was increased by 24% using low thermal conductivity fins of the reference case. While strong increase (54%) was obtained when high conductive fins were used. Nevertheless, with low conductive fins, full evaporation was achieved in 6 passes only (Figure 14). Accordingly, significant reduction by up to 50% or so can be obtained using the innovative porous media concept with low thermal conductivity fins. Up to 66% reduction in size can be achieved if high conductive fins ($k \geq 400$ W/mK) are used. This highlights the importance of finding highly conductive materials for high temperature applications feasible for fins production or porous media fabrication to replace the conventional fins. The expected significant increase in pressure drop was controlled under acceptable range by implementing porous media at effective location, which is the key parameter of this innovative concept.

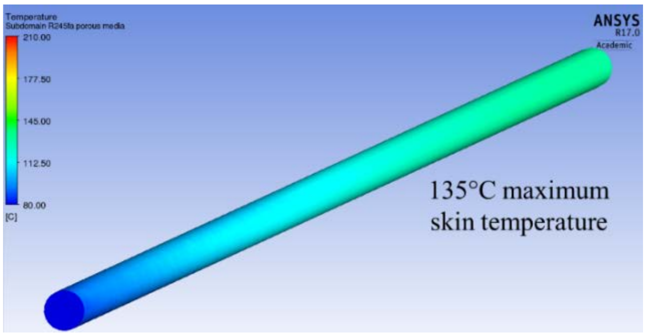


Figure 12 : Temperature contours of R245fa at the main pass influenced by high (470°C) gas temperature.

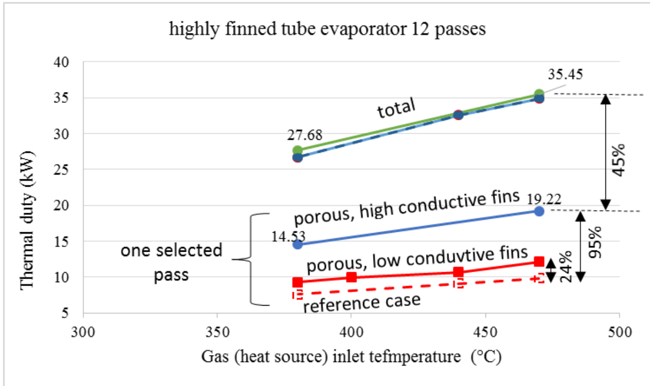


Figure 13 : Thermal duty of the 12 passes of the evaporator and at the major affected pass where porous media was implemented for two different fins type.

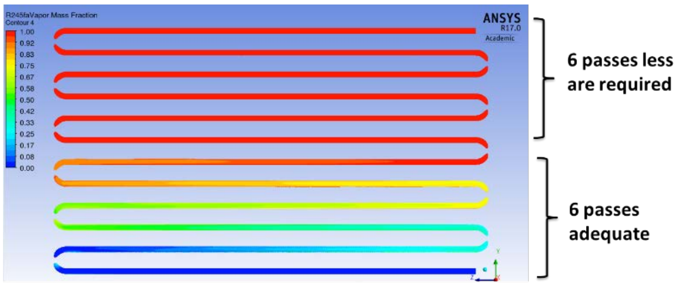
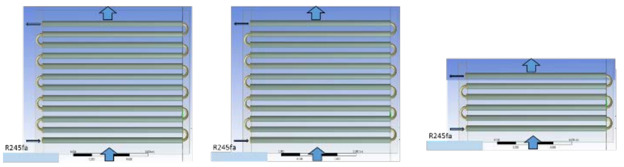


Figure 14 : Vapour quality contour at the 12 passes of the evaporator with porous media effectively implemented at the selected pass (low conductive fins).

4.4 Overall Comparison

An overall comparison was performed in evaporator size (Figure 15) and workable zone requirements (Table 5) between the reference case and that obtained with the two innovative concepts. It can be indicated that with the two innovative concepts no constraint was imposed on the workable zone. Thus, the privilege of using the non-flammable refrigerant R245fa at high temperature applications for maximum heat transfer was acquired. Accordingly, higher refrigerant/ gas inlet temperatures can be used to accelerate evaporation and decrease size. No additional equipment cost is required to meet high safety regulations imposed on flammable fluids, where additional mandatory regulations are imposed for much higher pressure utilization.



Reference evaporator   Intake air concept   Porous media concept

Figure 15 : Evaporator size of the reference design (left), intake air (middle), and porous media (right), for R245fa applications at high temperature heat source.

Table 5 : Overall comparison between the reference evaporator and that with the two innovative concepts.

Reference evaporator	Intake air concept	Porous media concept
Constraint workable zone	No constraint	No constraint
Risk of overheating and decomposition at high gas temperature> 400°C	No risk of overheating	No risk of overheating
No control	Controlled mixed stream inlet temperature below 400°C	No requirements
Larger size is required at gas temperatures 380°C. Higher temperatures not allowed	Potential to decrease size at high gas temperatures (> 500°C)	Potential to decrease size by up to 50% at gas temperatures ≥ 470°C

5. CONCLUSION

Under the studied conditions in this paper, high temperature application of the nonflammable refrigerant R245fa in direct heat extraction was effectively extended using two innovative concepts. Thermal performance was improved and key parameters influencing the process were determined, as follows:

- R245fa mass flowrate as well as gas temperature are key parameters in determining a safe working zone with no risk of overheating/decomposition.
- With innovative concept, harvested gas mixed with intake air, a safe working zone (380°C ≤ gas temperature ≥ 400°C) of a reference design can be effectively controlled and possible fluctuations in harvested gas temperature are mitigated.
- With innovative concept, open pores metal foam implemented in major row influenced by the high temperature heat source, hot spots were eliminated, no constraint was imposed on the working zone, and thermal performance was enhanced (by up to 24%).
- Using high conductivity (k ≥ 400 W/mK) fins in the second concept, thermal duty was doubled indicating that a significant decrease (50%) in evaporator size and cost can be achieved.

6. RECOMMENDATION

For higher temperature process heat applications (T > 500°C), evaporator performance and potential of size reduction with the two new concepts should be studied. The impact of different refrigerant mass flux on R245fa overheating should be assessed. Feasibility of implementing porous media inside more affected passes should be examined. Also, experimental examination for the pressure drop should be performed for validation. More research is required to find high conductive materials that tolerate high gas temperatures feasible for fins or porous media fabrications. Moreover, new evaporator geometries with porous media should be assessed.

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