Cambridge University Engineering Department
Engineering Tripos Part IIA
PROJECTS: Interim and Final Report Coversheet

IIA Projects

TO BE COMPLETED BY THE STUDENT(S)

Project:	GA4 – Heat Pump		
Title of report:	~~Group Report~~ / Individual Report (delete as appropriate)		
Name(s): (capitals)		crsID(s):	College(s):
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Declaration for: ~~Interim Report~~ 1 / ~~Interim Report 2~~ / Final Report (delete as appropriate)

I/we confirm that, except where indicated, the work contained in this report is my/our own original work.

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Grade	A*	A	B	C	D	E
Standard	Excellent	Very Good	Good	Acceptable	Minimum acceptable for Honours	Below Honours

Grade the reports by ticking the appropriate guideline assessment box below, and provide feedback against as many of the criteria as are applicable (or add your own). Feedback is particularly important for work graded C-E. Students should be aware that different projects and reports will require different characteristics.

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Guideline assessment (tick one box)

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Report	

GA4 Final Report

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1 Summary

R134a is a common refrigerant used in heat pump systems for domestic heating and refrigeration. It is, however, becoming outdated and new refrigerants have been developed with similar performance characteristics but less environmental impact. This report analyses a selection of "new" and "old" refrigerants in terms of performance, user safety, and environmental impact as well as investigating the transcritical CO_2 cycle for domestic heat pump applications.

The analysis uses representative weather data for Cambridge and is based on an average sized UK house connected to the National Grid. Numerical analysis of the selection of heat pump cycles and refrigerants is conducted using the `CoolProp` [3] library for `Python`.

2 Introduction

Due to the worldwide and growing threat that climate change poses to the whole of society, our CO_2 emissions must be reduced for the near and immediate future. A major source of CO_2 emissions in the UK and many other countries is domestic heating.

Traditionally in the UK, domestic heating is achieved using natural gas or oil boilers. With the introduction of condensing boiler technology, boiler efficiencies have increased significantly in the UK with all new boilers since 2018 being required to achieve an efficiency of more than 92%. However, many homes in the UK are not linked to the national gas network and therefore often run on oil based boilers which have much higher CO_2 emissions per kWh of heat supplied than natural gas. Furthermore many homes in the UK will be fitted with old and less efficient boilers than the ¿92% standard required by the UK government since 2018.

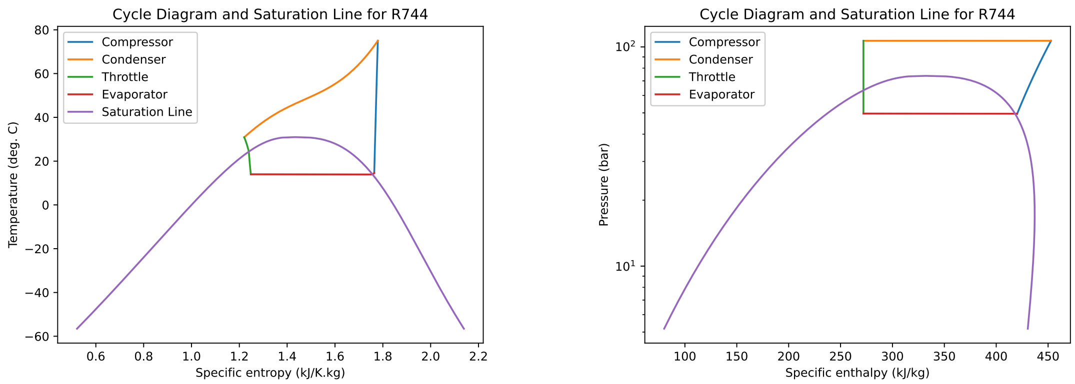
Heat pumps provide a way to meet domestic heating requirements whilst also theoretically reducing CO_2 emissions. Many different heat pump refrigerant fluids exist with unique advantages and disadvantages. A significant driving factor behind refrigerant development in the past tens of years is the Global Warming Potential (GWP) of the refrigerant. It is a measure of the equivalent quantity of CO_2 which would cause the same global warming effect so clearly refrigerants with a GWP significantly greater than 1 have a large global warming impact if released into the atmosphere due to system leaks/ failure or routine heat pump maintenance. Another key factor is the Ozone Depletion Potential (ODP) of the refrigerant. This is related to the refrigerant R11 and ranges from 0 (doesn't deplete the Ozone layer) to 1 (effect is as significant as R11). The ODP of a refrigerant is often increased by Chlorine content but the chemical reactivity of each refrigerant with Ozone can be more complex than this simple approximation.

2 new refrigerants which have been developed and proposed as a replacement for R134a are R1234ze and R1234yf. Both of these have lower GWPs and similar cycle characteristics which will be analysed later and is also reported by Nawaz et al. [8].

Recent developments are also investigating the suitability of the Transcritical CO_2 (R744) cycle for domestic heat pump applications and despite high condenser pressures Austin and Sumathay [2] report that the technology is promising for future applications. Furthermore, the refrigerant choice has many environmental benefits over older heat pump refrigerants such as R22 and R134a.

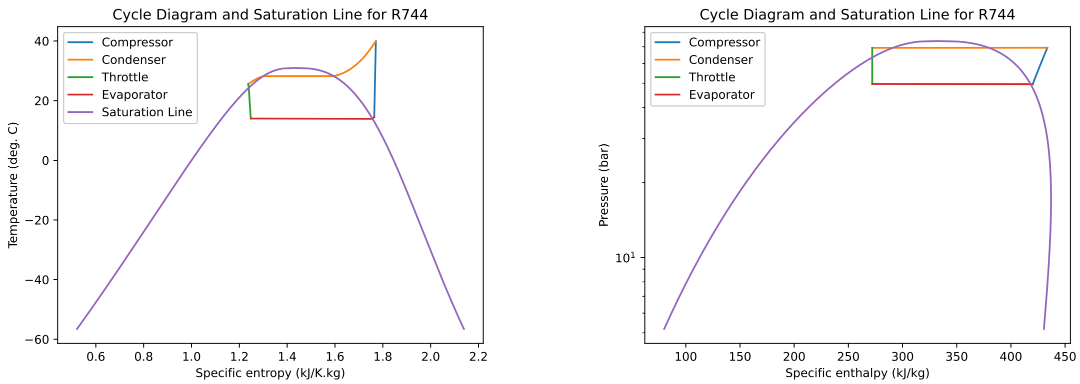
3 Refrigerant and Cycle Comparisons

3.1 Transcritical CO_2 Cycle



(a) T-s diagram (b) P-h diagram

Figure 1: Cycle Diagrams for the Transcritical CO_2 (R744) cycle with T evaporator = 14^oC, T hot water = 65^oC ,Compressor $\eta_s = 0.85$, Condenser P drop = $\frac{1}{20}$bar, Evaporator P drop = $\frac{1}{10}$bar, $h_1 - hsat_1 = 2kJ/kg$, and $h_4 - hsat_4 = 35kJ/kg$



(a) T-s diagram (b) P-h diagram

Figure 2: Cycle Diagrams for the Transcritical CO_2 (R744) cycle with T evaporator = 14^oC, T hot water = 30^oC ,Compressor $\eta_s = 0.85$, Condenser P drop = $\frac{1}{20}$bar, Evaporator P drop = $\frac{1}{10}$bar, $h_1 - hsat_1 = 2kJ/kg$, and $h_4 - hsat_4 = 35kJ/kg$

Unlike the subcritical heat pump cycle which was tested for R134a and all other refrigerants in this report, the transcritical CO_2 (R744) cycle has a condenser which operates outside the two-phase region of the fluid, as shown in Figure 1. For very low hot water temperatures required from the heat pump the condenser may also begin to operate in the two-phase region as shown by Figure **??** which is identical in cycle parameters to Figure 1 except that the hot water temperature from the heat pump has been reduced from 65 to 30^oC.

The COP for the cycle in Figure 1 is 5.53 whereas the COP for the cycle in Figure 2 is 11.99. As with subcritical cycles, it is clear that the COP increases as the temperature difference between the evaporator and condenser are reduced. This is displayed in Figure 3 below. The evaporator temperature for an experimentally tested heat pump was found to be 5K above the ambient air temperature and the refrigerant maximum condenser temperature is assumed to be 10K above the required hot water temperature to allow for an adequate rate of heat transfer.

Unlike for the subcritical cycles, the peak of COP does not occur when the ambient air temperature is as close as possible to the hot water temperature and in fact occurs at approximately 15^oC for a hot water temperature of 35^oC. This lends the transcritical cycle well to domestic heating applications where the temperature of the ambient air (i.e cold source) is often less than 20^oC and heating is not required for the home when the ambient air temperature is above 20^oC anyway as this is approximately the temperature of the inside of the average house. As can be seen from the COP surface in Figure 3, the transcritical R744 cycle would not be well suited to heating applications if the ambient air temperature were above 20^{o}C as this comes close to the critical temperature of CO_2 (31^{o}C) and therefore the cycle diagram on the T-s diagram becomes very tall and "skinny" and as such the COP is very low.

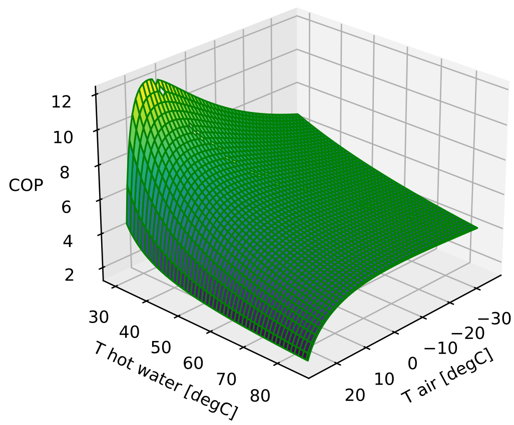


Figure 3: COP surface for the Transcritical CO_2 (R744) cycle with Compressor $\eta_s = 0.85$, Condenser P drop $= \frac{1}{20}$bar, Evaporator P drop $= \frac{1}{10}$bar, $h_1 - hsat_1 = 5kJ/kg$, and $h_4 - hsat_4 = 50kJ/kg$

3.2 Refrigerant comparisons

3.2.1 Performance

As can be seen from Figure 4 below, the maximum cycle pressure (which occurs in the condenser of the heat pump) is dependent on the hot water temperature required from the heat pump, as well as the refrigerant and cycle type. It is immediately clear that the transcritical R744 cycle operates at much higher pressures than the other subcritical cycles tested. This poses structural challenges for the condenser design but there are not unfeasible operating pressures and can be designed around.

Of the two proposed replacement refrigerants for R134a (R1234yf and ze), R1234yf has much closer condenser pressures to R134a at both a hot water temperature of 35 and 65^{o}C, corresponding to a condenser temperature of 45 and 75^{o}C, as discussed in Section 3.1. Because of this and other factors such as density as discussed by Nawaz et. al [8], R1234yf requires very little changes to an exisitng R134a heat pump to be used as a replacement refrigerant.

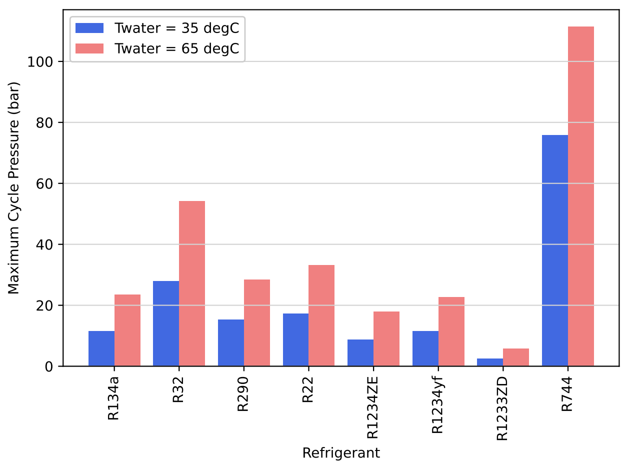


Figure 4: Maximum Cycle Pressures for subcritical cycles of different fluids and for the transcritical R744 (CO_2) cycle

3.2.2 Safety

There are 3 key factors to consider when considering the safety of a refrigerant to be used for a heat pump cycle.

The first of these is the flammability rating of the refrigerant. According to ASHRAE [1] designations, R134a and R744 receive the lowest flammability rating of 1 whereas R1234yf and R1234ze have a higher flammability rating of 2L which is more flammable but not posing significant danger unlike R290 (propane) which receives the highest ASHRAE flammability rating of 3 because it is a pure hydrocarbon. The flammability ratings are shown in Figure 5 below.

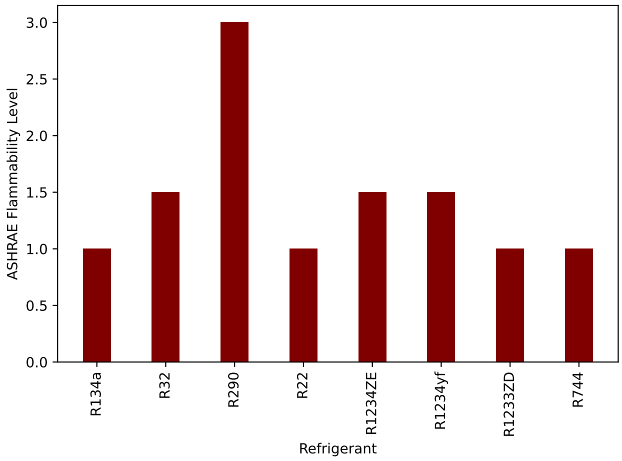


Figure 5: ASHRAE [1] flammability ratings of refrigerants, 2L rating = 1.5 in this graphic, 1 being minimum flammability rating, 3 being the maximum for the ASHRAE designation.

The second safety factor to consider is the toxicity of the refrigerant. All the refrigerants in Figure 5 have an ASHRAE toxicity rating of 1 which is effectively non-toxic in a (low) specified concentration in air. Clearly any refrigerant that isn't air can cause death in sufficient enough quantities that it replaces all oxygen in a room so that one cannot breathe but this is not what the ASHRAE toxicity ratings aim to cover.

Finally, the 3rd key safety factor is the maximum cycle pressure. It is clear that a heat pump operating with a higher cycle pressure is more likely to leak if not designed properly and as such these refrigerants may pose a higher risk if they are toxic or flammable. If they are not then a small leak will not cause any immediate human safety concern if they are outside so that refrigerant can disperse but may have a large environmental impact as discussed in the next section.

3.2.3 Environmental Impacts

As with safety there are 3 key factors to consider with regards to the environmental impact of a refrigerant. These are the Ozone Depletion Potential (ODP), the Global Warming Potential (GWP), and again the cycle pressure due to its influence on potential for a refrigerant leak.

All 4 refrigerants primarily discussed in this report [R134a, R1234yf, R1234ze and R744 (CO_2)] have an ODP of 0 therefore they do not react with and deplete the ozone layer.

The GWPs of these refrigerants are shown in Figure 6. It can be seen from this figure that the GWP of R134a is more than 2 orders of magnitude greater than R1234ze and R1234yf and of course the GWP of R744 (CO_2 is 1)

One final point of consideration when assessing the environmental impact of a certain refrigerant is that mixed refrigerants such as R410a are much harder to recover and recycle at the end of a heat pumps life than pure refrigerants such as R134a, R1234yf, and R1234ze, all of which are pure compounds so this has little impact on their respective environmental impacts.

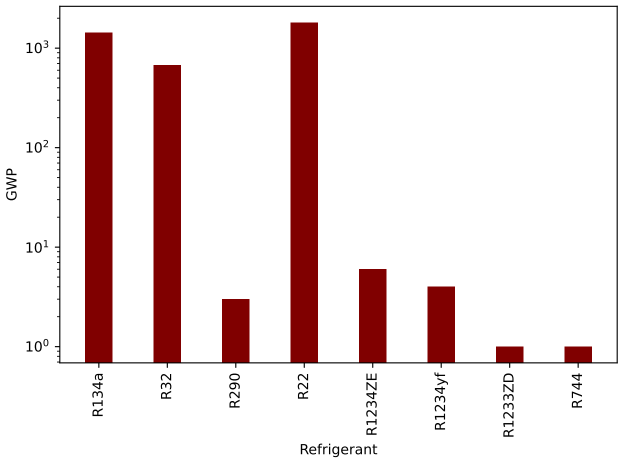


Figure 6: GWP [5] of refrigerants discussed.

4 Yearly Performance

4.1 Daily Heating Requirement

By modelling different boundaries of the house as boundaries with different U-values as in MacKay's 'Sustainability without the hot air' [4], it is possible to estimate the daily heating requirement of an average UK house [7] of total floor area $96m^2$ over 2 floors. It is approximated that 30% of the house wall area is double glazed windows and doors and that all air in the house changes every hour.

Element	**Area (m^2)**	**U-value (W/m^2/K)**	**Contribution to heat loss Coeff. (W/K)**
Roof	48	0.4	19.2
Floor	48	0.8	38.4
Walls	98	0.6	58.5
Windows	42	3	126
	Volume (m^3)	**Air Changes / hr**	$(NV/3)$
Ventilation	240	1	80
			322.4

Table 1: Evaluation of UK average house heat loss coefficient

4.2 Seasonal Performance Factor

The seasonal performance factor of each different heat pump can be calculated by dividing the total heat supplied to the home over a year by the electricity input.

Hot T_w (^{o}C)	Comp Power Cap (W)	Fluid	SPF
35.0	1000	Transcritical R744	8.8
		R134a	4.4
		R1234ZE	4.3
		R1234yf	4.0
		R1233ZD	4.1
	No	Transcritical R744	8.8
		R134a	5.1
		R1234ZE	5.0
		R1234yf	4.8
		R1233ZD	4.9
65.0	1000	Transcritical R744	5.3
		R134a	1.9
		R1234ZE	1.9
		R1234yf	1.7
		R1233ZD	2.1
	No	Transcritical R744	5.5
		R134a	2.7
		R1234ZE	2.7
		R1234yf	2.4
		R1233ZD	3.0

Table 2: Seasonal Performance Factor (SPF) over one year for different heating methods

4.3 Yearly CO_2 emissions

Hot T_w (^{o}C)	Comp Power Cap (W)	Fluid	CO2 emissions (kg/yr)
35.0	1000	Transcritical R744	323
		R134a	645
		R1234ZE	661
		R1234yf	703
		R1233ZD	689
	No	Transcritical R744	323
		R134a	557
		R1234ZE	564
		R1234yf	585
		R1233ZD	577
65.0	1000	Transcritical R744	531
		R134a	1486
		R1234ZE	1512
		R1234yf	1697
		R1233ZD	1366
	No	Transcritical R744	514
		R134a	1039
		R1234ZE	1057
		R1234yf	1196
		R1233ZD	960
		Natural Gas Boiler	**3960**

Table 3: Annual CO_2 emissions (kg) for different heating methods

4.3.1 Standard Condensing Boiler

To calculate the yearly CO_2 emissions of a natural gas boiler from Table 3, the composition of UK natural gas is approximated as 100% methane. Assuming stoichiometric combustion in the boiler gives $2.75kgCO_2/kg$ natural gas burnt. The average gross calorific value of UK mains natural gas is $14.6kWh/kg$ [6]. The CO_2 emissions from the natural gas boiler (assuming a 92% efficiency as mentioned in 2) is therefore $204.7gCO_2/kWh$ heat supplied. It is assumed that the boiler efficiency and therefore CO_2 intensity do not change regardless of the hot water temperature (35 or 65 ^{o}C for this analysis).

5 Conclusions

For the reference Cambridge weather data, and assuming a desired house temperature of 18^{o}C, the transcritical R744 cycle performed far better than both R134a, and the R1234yf and R1234ze replacements tested for a hot water temperature of 65^{o}C for radiators and 35^{o}C for underfloor heating. It is also a very favourable refrigerant in terms of its GWP of 1 and ODP of 0. It does have a much higher condenser pressure than the refrigerants operating on sub-critical cycles but technology is improving to handle the higher condenser pressures and small leak rates are not a severe issue due the refrigerants low toxicity, flammability, GWP, ODP, and cost. Additionally, from Tables 2 and 3, it is clear that the transcritical CO_2 cycle has a higher heating capacity for a given compressor input power owing to its much higher COP for the tested temperature ranges.

Of the two low-GWP replacements tested for R134a (R1234yf and R1234ze), R1234ze performed marginally better in terms of SPF and annual CO_2 emissions however, R1234yf had much closer condenser pressures to R134a as confirmed by Nawaz et. al. [8] can be used as a replacement for R134a with "no or very minimal changes" to the heat-pump system whereas R134yf would require a "larger compressor displacement to achieve a similar water heating capacity to R134a". Both R1234yf and R1234ze have significantly lower GWPs than R134a and considering that their annual SPF and CO_2 emissions are very similar to R134a, both would make a good replacement to R134a heat pumps but ideally a transcitical R744 cycle would be even more preferrable in the UK.

Finally, it is clear from Table 2 and 3 that when operating a heat pump for heating rather than a natural gas (or oil) boiler, it is far more beneficial to operate the home heating system at a lower water temperature such as 35^{o}C which is typical for hot water underfloor heating. On the other hand, very little benefit is seen in annual CO_2 emissions if this change is made to a boiler operated system. For this analysis we have assumed the boiler efficiency is not dependent on hot water temperature and therefore very little effect is seen whereas the COP of a heat pump has a strong temperature dependence.

6 Bibliography

References

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