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# Coupling of engine exhaust and fuel cell exhaust with vapour absorption refrigeration/air conditioning systems for transport applications: A Review

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## Abstract

Using the residual heat from the engine exhaust and of late from the fuel cell exhaust to drive a refrigeration or air conditioning unit on-board a vehicle has been the interest of many research groups worldwide. Umpteen number of modelling studies and a few prototypes have been built in this area. In this paper, an up to date review of the heat driven absorption refrigeration/ air conditioning systems specifically meant for transport applications is given. This is followed by a discussion on the major challenges involved in implementing such a technology for the transport sector, the ways in which such a technology can be developed further and why using heat driven refrigeration/air conditioning systems could be a game changer in the automotive industry. From the study carried out two things are apparent – there is currently no VARS unit that can readily be used on-board vehicles and linking VARS units with engine exhaust leads to drop in engine efficiency and thus overall vehicle performance. Fuel cells (SOFCs in particular), if used as APUs can reduce the load on the engine and also supply a constant heat load to the VARS and thus be more effective.

**Keywords**: Residual heat, Fuel Cells, Absorption refrigeration, Refrigerated Trucks

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# List of Abbreviations/Symbols

APU – Auxiliary Power Unit
AWCC – Ammonia Water Cogeneration Cycle
CHCP – Combined Heat Cooling and Power
CHP – Combined Heat and Power
COP – Coefficient of Performance
COG – Coke Oven Gas
DAR – Diffusion Absorption Refrigerator
DCC – Direct Contact Cooler
EV – Electric Vehicle
GWP – Global Warming Potential
HCCI – Homogenous Charge Compression Ignition
HEV – Hybrid Electric Vehicle
HTPEFC – High Temperature Polymer Electrolyte Fuel Cell
MCFC – Molten Carbonate Fuel Cell
PAFC – Phosphoric Acid Fuel Cell
PEFC – Polymer Electrolyte Fuel Cell
RPM – revolutions per minute
SOFC – Solid Oxide Fuel Cell
TRU – Truck Refrigeration Unit
VARS – Vapour Absorption Refrigeration System
VC – Vapour Compression

# 1 Introduction

Refrigerated transportation plays a vital link in the cold chain because there is a need for transporting foods (also certain goods like plants and pharmaceuticals) securely from the place where they are sourced to their ultimate destination – the consumers. Figure 1 shows the schematic of the cold chain process and the need for refrigerated transportation at different stages.

As seen in Figure 1, refrigerated transportation takes centre stage by linking many steps between the supplier and the consumer. Without proper and adequate refrigerated transport, food and medicine supply chains would simply break down. It is even more essential these days as the distance between producers and consumers is increasing and the demand for seasonal products to be available all year round is also increasing. It is only because of proper refrigerated transport that consumers are able to enjoy foods produced elsewhere in the world. Consumers demand foods of the highest quality which is again one of the driving factors for food companies to opt for refrigerated transport [1]. Air conditioning on the other hand is not as vital to the food transport process as refrigeration, however it is an essential feature that is made available on all current vehicles.
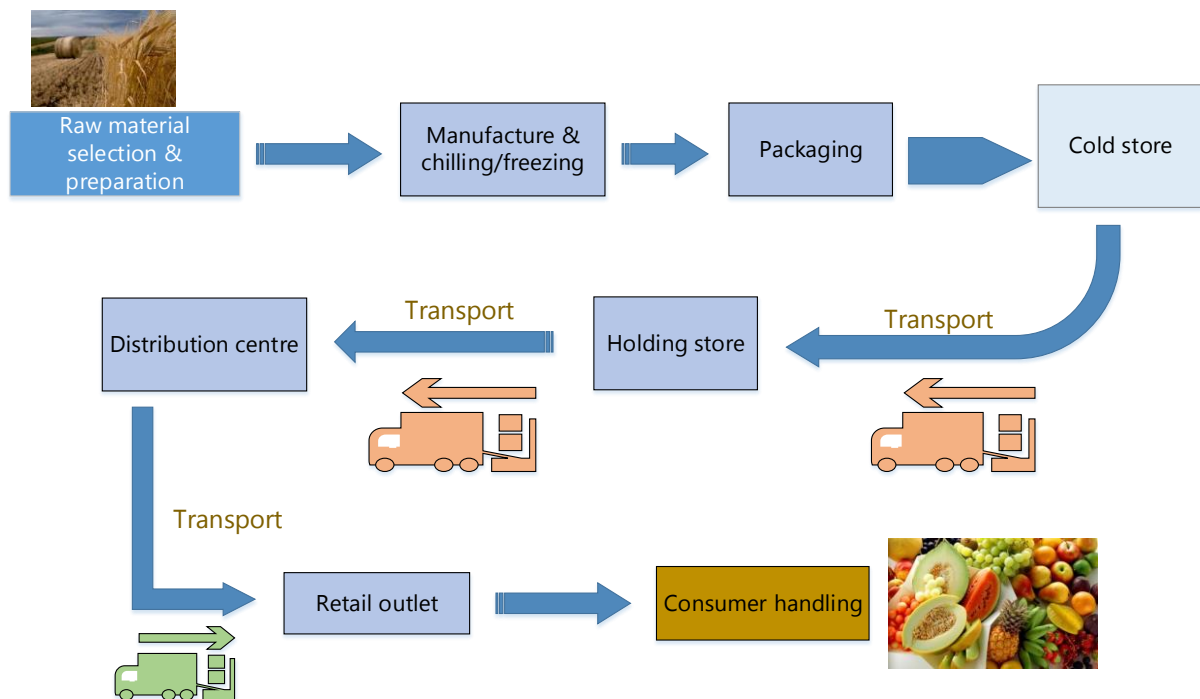


Figure 1: Block diagram representation of the cold chain process

In the EU, refrigerated vehicles are generally divided into three categories namely: small vans (up to 3.5 tonnes), medium rigid trucks (up to 32 tonnes) and large articulated vehicles (up to 44 tonnes). Refrigeration duty of a small van, medium truck and articulated vehicle is 3000 W and 5000 W, 7500 W and 13500 W, 9500 W and 17500 W at -0$^{o}$C and -20 $^{o}$C of transportation temperature respectively. There are particular temperature constraints for certain types of food as shown in Table 1 [2]. Hence, it is required to maintain the specific temperature in order to ensure good shelf life of food products.

Table 1 Temperature requirements for the transportation of different food products [2]

| Food products | Temperature requirement ($^{o}$C) |
|---|---|
| **Chilled** | |
| Meat | +3 |
| Milk, cheese, curd and cream | +3 |
| Fresh fish | +2 |
| Sweet dishes and eggs | +3 |
| **Frozen** | |
| Ice and ice cream | -25 |
| Fishery products | -18 |
| Deep frozen foods | -18 |
| Butter and edible fats | -14 |

One of the greatest challenges facing refrigerated vehicles is their heavy dependence on oil (diesel) for both refrigeration and traction purposes [3]. Most of the refrigerated vehicles are powered by internal combustion engines and the refrigeration units on board are either directly or indirectly linked to them. This means irrespective of the scenario whether the vehicle is moving or not, the diesel engine on-board the vehicle needs to be running at all times which leads to wasteful diesel consumption and increased emissions (of greenhouse gases). Truck Refrigeration Units (TRUs) operate in much harsher environments than stationary refrigeration units. This, along with other factors, reduces the efficiency of TRUs [4]. On-board refrigeration can account for up to 40 % of the total vehicle fuel consumption [5, 6] and on-board air conditioning can increase fuel consumption by

20% [7, 8]. This is because the compressor of the Vapour Compression (VC) system increases the load on the engine which in turn increases the fuel consumption, emissions and operating temperature of the engine. The most prominent refrigeration system used on trucks is the VC system and the refrigerant used in it is mainly R404A, R134A or R410A. These refrigerants have a high Global Warming Potential (GWP) and the annual refrigerant leakage rate from these units can be as high as 25% [3, 9].

The above mentioned issues with conventional refrigeration/ air conditioning systems has sparked increased interest in developing alternate refrigeration systems and more eco-friendly refrigerants in order to reduce the load on the main engine, reduce emissions and achieve a higher overall efficiency.

There are various alternate refrigeration technologies available [10] but heat driven refrigeration/air conditioning systems has attracted considerable interest for implementation on the vehicle because there is a lot of waste heat that is being rejected to the ambient from the vehicle. The source of the waste/residual heat is either the engine exhaust (in conventional vehicles) or fuel cell exhaust (if fuel cells are used on-board). The only thermally driven refrigeration systems are the *sorption refrigeration systems* which comprise of *adsorption* and *absorption* systems and *ejector refrigerator systems*. Ejector refrigeration systems are able to achieve refrigeration temperatures above 0 $^{\circ}$C but not sub-zero temperatures [10] and adsorption systems need complex adsorbent beds which are bulky and expensive. In the light of these issues with ejector and adsorption systems, most of the research groups have looked into developing absorption refrigeration systems suitable for transport applications. Absorption refrigeration systems also have a higher COP when compared to ejector and adsorption refrigeration systems and are able to achieve sub-zero temperatures.

In an effort to provide a holistic view on the above topic, a detailed review of the absorption refrigeration technology development for transport applications, coupled to engine exhaust and fuel cell exhaust is presented in this paper.

# 2 Absorption refrigeration systems coupled to engine exhaust

Figure 2 represents the schematic of a heat driven vapour absorption refrigeration system (VARS). It consists of a desorber, rectifier, absorber, solution heat exchanger, condenser, refrigerant heat exchanger and evaporator. In VARS, the mechanical compressor of the conventional vapour compression refrigeration system is replaced by a thermal compressor and absorbent.
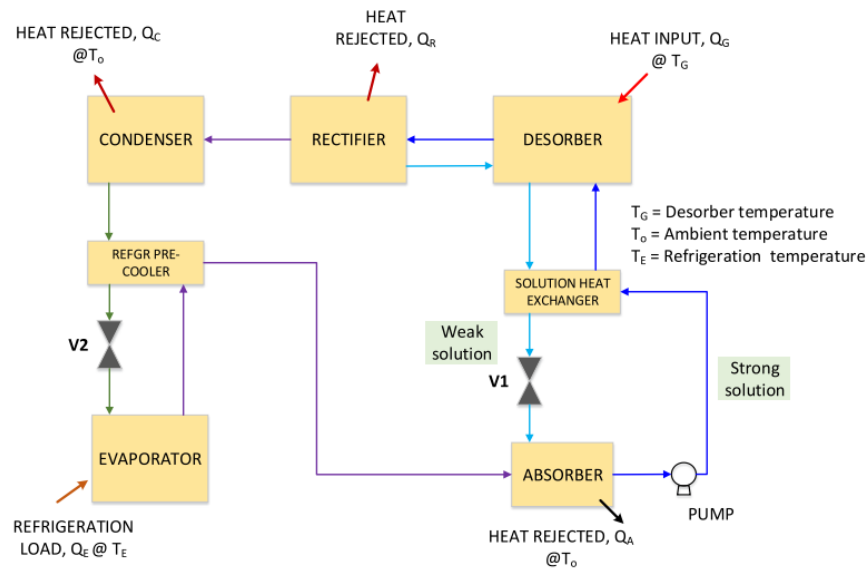


Figure 2 Schematic of vapour absorption refrigeration system [11]

For the successful commercialisation of the VARS for automobile applications, it is essential to develop less bulky and compact unit that can be housed within the available packaging volume on the different types of vehicles. Staedter and Garimella [12] developed compact VARS based on microchannel heat exchanger technology with a cooling capacity of 7 kW as shown in Figure 3. The overall volume of the developed system was 0.28 $m^3$ (with dimensions of 0.66 m x 0.66m x 0.66 m). Venkataraman et al [13] mentioned that the packaging volume available for small, medium and large refrigerated trucks are 0.44 $m^3$ , 0.9 $m^3$ and 2.73 $m^3$ respectively. Hence, looking at the volume numbers, it seems possible to employ VARS on the refrigerated trucks.

Figure 3 Compact VARS developed by Staedter and Garimella [12]

The idea of using VARS for a refrigerated truck has already been explored by researchers albeit with less success. On a conventional truck, powered by a diesel engine, the source of residual thermal energy is mainly from two places – the *engine exhaust* and the *engine cooling loop*. The exhaust gas is in the temperature range between 250 $^{o}$C and 490 $^{o}$C depending on the engine RPM and engine torque and contains $NO_x$, $SO_2$ and hydrocarbons and is quite corrosive and harsh on metals that come in contact with it. With the flow rates and temperatures involved (of the exhaust), a considerable amount of thermal energy can be tapped from it. The engine coolant on the other hand is usually a mixture of water and ethylene glycol or propylene glycol and its temperature is between 100 $^{o}$C and 130 $^{o}$C. The heat of the engine block is usually rejected in a radiator. The coolant flow rate is less compared to the engine exhaust flow rate [14] but the very fact that coolant is a liquid gives it higher thermal capacity than the exhaust gas. The reason why engine coolant has not been used to drive the VARS on the vehicle is due to low flow rates and small temperature change when coupled to heat exchangers of VARS thereby reducing the effectiveness of the heat exchanger below practical considerations.

Almost one third of the chemical energy of the fuel is carried away by the exhaust stream of the vehicle [15-17] and another one third by the coolant loop and this has attracted considerable research in making use of the residual thermal energy available from the vehicle to drive the VARS. On the vehicle, the VARS can either be used for a refrigeration system or for an air conditioning system. The

evaporator temperature for air conditioning purposes lies between +10 and +15 $^{o}$C and that for refrigeration purposes is between -20 $^{o}$C and +5 $^{o}$C, depending on the product being transported [18].

In order to develop an alternate refrigeration system for trucks or other mobile applications there is a need to design and develop compact high performance components in the volume space available on board the vehicle. Prototype development or table top demonstration is the way forward for investigating the suitability and adaptability of any new system for an application that is currently catered by a conventional system. In light of that, very few research groups have carried out experimental investigation or prototype development of an engine exhaust heat driven VARS and even among them very few have developed an integrated VARS box which can be fitted on the vehicle. Most of them have focussed only on theoretical studies and modelling where every component of the VARS was treated like a black box [19-22]. Although information on mass flows, energy flows and concentrations are crucial for design of individual components, the technology cannot be taken forward unless there is a working prototype or a comprehensive modelling study of each and every component along with the blueprint of its geometrical details. A brief summary of the experimental and theoretical work carried out in this field to date is presented here.

## 2.1 Experimental and prototype work

### 2.1.1 Refrigeration application

Koehler et al [15] developed a prototype of an absorption refrigeration unit, based on $NH_3 - H_2O$ working pair for a 40 tonnes truck (volume: 13.6 x 2.6 x 2.8 m$^3$ ) trailer application, which utilised heat from the exhaust gases of the vehicle. They achieved COP values between 0.23 and 0.3 for the initial un-optimised system but suggested there is scope for increasing it by 25 %. They were able to achieve a cooling capacity of 6 kW at an ambient temperature of 30 $^{o}$C and a cooling capacity of 8.5 kW at an ambient temperature of 20 $^{o}$C for a refrigerated cabinet temperature of -20 $^{o}$C. This was close to the German Industrial Standard (DIN 8959) which specifies a typical cooling load requirement of 5.7 kW for a truck trailer for an ambient temperature of 30 $^{o}$C and a refrigerated

temperature of -20 $^{\circ}$C. DIN 8959 is the guideline to determine the refrigeration duty of insulated food carriers. It also takes into account the additional refrigeration duty due to door opening of the truck for loading and unloading of food products. They also stated that since in a VARS the concentrations of the solutions (weak and strong) are fixed, the COP cannot be varied that much and it is extremely difficult to build a VARS with variable concentrations.

Horuz [23] integrated a VARS with the engine exhaust and proved that the concept is indeed feasible. He used a Robur Servel ACD – 3600, a commercially available VAR unit based on $NH_3 – H_2O$ working pair which had a cooling capacity of 10 kW and integrated it with the exhaust of a Ford 150 (Dover) 6 litre turbo diesel engine. He however did not integrate the system on the vehicle but rather carried out the experiment on a test bench and concentrated on two aspects - a plenum chamber design for exhaust flow around the desorber and engine performance when the VARS was connected to the exhaust. The plenum chamber had a direct effect on the engine performance. When the chamber with a large flow area was connected to the exhaust; engine back pressure, fuel consumption and engine efficiency was not affected. On the other hand, when the chamber with a smaller flow area was connected to the exhaust, the engine back pressure was higher which resulted in higher fuel consumption and in turn lower engine efficiency. Hence the flow chamber for the exhaust gas around the desorber of the VARS had a major influence on performance of the engine and was recommended to be designed in such a manner so as to have a similar pressure drop profile as that of a normal engine exhaust system.

Horuz and Callander [24] specified details of the type of heat exchangers used for major components used on VARS. A major finding was that the VARS unit worked more efficiently when the condenser and absorber were cooled separately. They recommended maintaining the condenser cooling source temperature lower than the absorber cooling source temperature in order to increase the cooling capacity of the VARS.

Another experimental piece of work on integrating a VARS unit with the engine exhaust was performed by Manzela et al [25]. They used a 1.6 L, 8 valve 4 cylinder engine along with a domestic

absorption refrigerator for their study. The engine was operated at 1500 rpm because they found that at higher engine RPMs excessive thermal energy was transferred to the refrigerant which prevented complete condensation of it in the condenser. They were able to achieve refrigeration temperatures between 5 $^{\circ}$C and 13 $^{\circ}$C and this was dependent on the percentage of valve opening between the engine exhaust and the desorber. The wider the opening, the lower was the refrigeration temperature. The prototype developed had a maximum cooling capacity of 18.4 W (which is extremely low) when the valve was completely open. The COP and the cooling power behaved in a totally opposite manner with the percentage of valve opening. A higher percentage of the valve opening resulted in a higher cooling capacity but a lower COP because of increased thermal energy available from the exhaust. They concluded from their experiments that the percentage of valve opening need not be 100% and that keeping it at 25 % was more than sufficient to cater to the needs of the absorption refrigeration system. The maximum COP achieved was 0.049 which was way below than what can theoretically be achieved.

**2.1.2 Air conditioning application**

Khaled et al [5] designed and fabricated a shell and tube heat exchanger as a desorber for use in an automobile air conditioning system where hot exhaust from the engine flowed through the shell and the $NH_3$-$H_2O$ solution flowed through the tubes. It had a heat load capacity of 4.6 kW, had a surface area of 0.196 m$^2$, and could fit in a space of 50 cm x 25 cm x 15 cm. Besides specifying the mechanical design of the generator (also known as desorber), the actual performance of the generator in terms of quantity of refrigerant desorbed and the heat and mass transfer aspects to the refrigerant absorbent solution were not specified. Hence, it remains unclear if the desorber could actually cater to the required cooling load. In another study by Khaled [26], the entire air conditioning system was connected to the exhaust of a 4 cylinder engine. The size of the system designed was not suitable for automotive use due to space constraints on the vehicle.

Ismail Hilali [27] designed a VARS prototype based on $H_2O$-LiBr working pair with a cooling capacity between 2 and 2.5 kW. A 1.3 L internal combustion engine was employed whose exhaust was coupled to the desorber of the VARS. Like Koehler et al [15], he too used a mixing chamber prior

to an air cooled absorber. He investigated the performance of the engine when it was coupled with the absorption refrigeration unit and also evaluated the performance of the absorption refrigeration unit as such. With such a custom built prototype, an evaporator temperature close to 11 $^o$C was achieved at a COP of 0.78. The COP is a function of many different parameters viz. desorber temperature, evaporator temperature, condenser temperature and absorber temperature. Hence a delicate balance is required to maximize the COP of the absorption refrigeration unit. Once again, with increase in engine RPM, the evaporator cooling capacity increased. This is because the heat recovered from exhaust gases increased which in turn allowed the overall COP to increase. The waste heat available from the engine ranged from 3 kW at idling RPMs to a high value of 18 kW at full load conditions. However, for the engine used in this study, the efficiency decreased after an RPM value of 2750. Hence the maximum heat recoverable while maximizing engine efficiency was around 9 kW. The engine suffered from back pressure effects when the desorber of the VARS was coupled to the engine exhaust and because of this the fuel consumption of the engine increased and its efficiency decreased. Hilali [27] suggested designing the desorber with minimum pressure drop and maximum heat transfer efficiency which would lead to a greater cooling effect even at lower engine speeds. As the cooling capacity was reduced when the vehicle was idling or when stationary, employing a backup gas burner at the desorber was recommended.

Talom and Beyene [6] coupled a 2.8 L V6 turbocharged internal combustion engine with a 10.55 kW Robur ACF-3600 absorption chiller and evaluated the system performance and responses both at part load and variable load conditions. The absorption chiller was modified; the original gas burner that supplied heat at the desorber was replaced with a plenum that channelled the hot engine exhaust. Under part load conditions and at an ambient temperature of 29.5 $^o$C, the absorption chiller was able to produce chilled water down to a temperature of 12 $^o$C when the engine RPM was 2400. A dynamic study was performed on the absorption chiller and the time taken by the absorption chiller to produce chilled water was calculated to be 14 minutes. At a higher engine RPM of 2800, the time taken by the absorption chiller to produce chilled water was almost half the previous. At variable load conditions, the chiller was able to produce chilled water as low as 6 $^o$C at an ambient temperature of 18 $^o$C. Other

than specifying the temperature of the chilled water achieved, no further details on the coupling between the internal combustion engine and the absorption chiller were provided.

Bux and Tiwari [28] coupled the exhaust from a diesel engine directly into a plate heat exchanger desorber (using a $H_2O$-LiBr working pair). The remaining components of the VARS were not included in the test set up. Although the objective of the research was focussed towards developing an air conditioning system for a passenger vehicle based on VARS technology, no specific details of the cooling load or the plate heat exchanger desorber, nor the desorber's capability to produce sufficient refrigerant were specified. Critical data needed for the system design was missing in the article. Direct coupling of the hot exhaust gases with the desorber, as carried out by these authors, is usually not recommended due to temperature incompatibility and possibility of corrosion.

Boatto et al [17, 29] discussed a more pragmatic approach for developing VARS as an alternate to the VC system for air conditioning. They stated that every part must be designed and manufactured with appropriate functional and geometrical characteristics owing to the limited space available on the vehicle and retrofitting commercially available VARS on the vehicle was not preferred. Their analysis was for a passenger vehicle and they recommended having storage vessels on board, for water and LiBr salt, to increase the system's capability of providing air conditioning at all times. Surplus thermal energy was available from the engine when it was operated above 3700 rpm and there was a need for employing an auxiliary burner when the engine output was less than 10 kW and if thermal energy storage was not provided. Their research work was split in two parts, the first part analysed the engine performance characteristics and the second discussed the layout and components involved in the VARS. Air cooled components (for condenser and absorber) were recommended due to space constraints. No detailed performance characteristics of the VARS were given however a self-support threshold of 6 kW as the minimum engine output was identified to sustain operation of the VARS using thermal energy recovered from the exhaust.

Hilali and Söylemez [30] fabricated an air cooled LiBr-$H_2O$ based VARS powered with an engine exhaust. Maximum capacity of VARS was 2.5 kW with 1.3 L engine coupled to VARS. The authors also characterised VARS performance as well as the engine performance. Maximum COP achieved in

the study was 0.78 at evaporator temperature of 11 °C.  It was observed that the cooling capacity of the VARS increases with rpm of the engine as flow rate of exhaust gas also increases with rpm therefore more heat can be recovered. During idling scenario of the engine, 3 kW of heat was recovered and under full load condition 18 kW of heat was recovered. The authors found that the VARS depicted optimum performance when heat recovered from exhaust was ~9 kW.  Further, it was concluded that the generator with minimum pressure drop and maximum effectiveness can enhance cooling load even at low engine speed. However, the authors also concluded that the back pressure generated due to the coupling of VARS with the engine exhaust results in higher fuel consumption and thus lower engine efficiency.

Kaewpradub et al [31]  carried out experiments on single effect LiBr-$H_2O$ based VARS coupled with engine exhaust of a 4-stroke gasoline engine. They provided detailed information on types of heat exchanger used for different components of VARS. They  conducted experiments at engine speeds of 1000, 1200, 1400 and 1600 rpm and found that the engine operation between 1200 and 1400 rpm is the most suitable to run the VARS.  It was determined that the speed above 1600 rpm accelerates the probability of  crystallisation of the LiBr-$H_2O$ solution due to higher temperature of the exhaust which in turn increases the generator temperature.  At 1400 rpm, highest COP of 0.275 and cooling load of 700 W were achieved.

Details of the individual components used for the VARS prototype, designed and built by the above experimental research groups are collated in Table 2.

Table 2: Details of components used in VARS for experimental prototypes

| VARS components | Koehler et al [15] | Horuz et al [23] | Manzela et al [25] | Khaled et al [5] | Hilali [27] | Talom & Beyne [6] | Sohail Bux & Tiwari [28] | Boatto et al [17, 29] | Kaewpradub et al [31] | Hilali and Söylemez [30] |
|---|---|---|---|---|---|---|---|---|---|---|
| **Desorber** | Plate fin | Closed steel cylinder with provisions for side heating from a natural gas burner and lower part being finned | Not specified | Shell and tube | Shell & tube | Not explicitly specified but absorption chiller model and manufacturer was given. Robur ACF-3600 | Plate heat exchanger | Plate heat exchanger | Spiral fin-and-tube heat exchanger | Shell and tube heat exchanger |
| **Rectifier** | Column filled with stainless steel pall rings | Coil in coil type | Not specified | Not specified | Not used | | Not specified | Not used | Not used | Not used |
| **Absorber** | Fin and tube & air cooled | Plate & fin type with air cooling | Not specified | Not specified | Car radiator with aluminium tubes and fins & air cooled | | Not specified | Finned tubes & air cooled. | Shell and coil heat exchanger | Finned type heat exchanger |
| **Condenser** | Fin and tube & air cooled | Plate & fin type with air cooling | Not specified | Not specified | Aluminium finned tube & air cooled | | Not specified | Finned tube & air cooled | Shell and coil heat exchanger | Finned type heat exchanger |
| **Evaporator** | Fin and tube, with steel tubes and aluminium fins | Coiled tube type with ethylene glycol sprayed over it | Not specified | Not specified | Aluminium finned tube & air cooled | | Not specified | Finned tube & air cooled | Shell and coil heat exchanger | Finned type heat exchanger |
| **Solution Heat Exchanger** | Plate fin made of stainless steel | Not used | Not specified | Not specified | Brazed plate heat exchanger | | Not specified | Not specified | Not used | Plate heat exchanger |
| **Refrigerant Heat Exchanger** | Plate fin made of aluminium | Concentric tube in tube design | Not specified | Not specified | Not used | | Not specified | Not specified | Not used | Not used |
| **Mixing vessel** | Column filled with pall rings | Not used | Not used | Not specified | Stainless steel column | | Not used | Not specified | Not used | Not used |
| **Sub cooler** | Fin and tube & air cooled | Not used | Not used | Not used | Not used | | Not used | Not specified | Not used | Not used |
| **Solution cooled absorber** | Not used | Simple pot with a coil inside | Not used | Not used | Not used | | Not used | Not specified | Not used | Not used |

Experimental research on the use of VARS as an alternate to the VC system is very scarce, with just a few research groups [5, 6, 15, 23-29, 32] carrying out prototype development or building a table top model. Even among these research groups, half of them have concentrated on the refrigeration aspect and the other half on the air conditioning aspect for the vehicle. Only two research groups [15, 23] have actually tried constructing a prototype from scratch and only Koehler et al [15] successfully integrated it on the vehicle but the efficiency was very low. Other than Boatto et al [29] no other experimental research group were able to design and develop a compact VARS for air conditioning applications. Hence, there is a need for more experimental research in this field if VARS is to be made as an alternate refrigeration unit for trucks/mobile applications.

Besides employing single stage VARS unit for coupling with engine exhaust, a few research groups have tried coupling *Diffusion Absorption Refrigerator* (DAR) with the engine exhaust and their work is briefly summarised below.

Aly et al [32] coupled a diffusion absorption refrigerator (DAR) with the exhaust of a diesel engine. The DAR employed was a commercially available one from Electrolux, model RAK 662, which had a total weight of 41 kg and had dimensions of 0.95 x 0.59 x 0.53 $m^3$. The engine employed was a Ford XLD 1.8 L 8 valve 4 cylinder engine which can deliver a maximum power of 44 kW. The obtained cooling power was varying between 3.2 W and 19.5 W. Detailed specifications of different components used in the DAR were given and the authors used direct coupling at the desorber of the VARS where the heat from the exhaust was directly used. As observed with many authors, the engine exhaust temperature is directly linked with the engine rpm and increasing the rpm increases the exhaust temperature. Hence in order to maintain the exhaust temperature around 200 $^o$C, the authors kept the engine RPM constant at 1750 rpm. Their prototype could achieve refrigeration temperature between 10 and 14.5 $^o$C and they concluded that controlling the exhaust mass flow rate of the exhaust was crucial.

Rego et al [33] designed a control system for regulating the engine exhaust to the desorber of the VARS. They employed a diffusion absorption refrigeration system based on $NH_3$-$H_2O$ working pair and modified the original LPG burner with the exhaust from an engine. The control system developed by them consisted of two valves, one permitting flow to the desorber and the other venting any remaining exhaust to the ambient. The valves were controlled via stepper motors and the control algorithm was based on PID control. With such a control strategy, they were able to achieve satisfactory performance of the VARS for a range of engine RPMs and engine torques except when the vehicle was idling. This shows that control plays a key role in thermally driven refrigeration systems and coupling the engine exhaust without a control mechanism would lead to poor performance.

Lin et al [34] also coupled a commercially available diffusion absorption refrigerator (DAR) with the exhaust of a diesel engine and concluded that the waste heat from the exhaust of the diesel engine was sufficient to drive the DAR only when the engine load was greater than 50%. The diesel engine employed by them was a Lister- Petter T series 9.5 kW diesel engine which was air cooled. The COP of the whole system was quite low, around 0.034. The whole set up was not made specifically for an automotive application but just to test the feasibility of coupling and working of the DAR with engine exhaust.

Most of these authors referenced above have also recommended that further research needs to be carried out in the following areas in order to make VARS an alternative to VC systems on-board vehicles:

  i)   Evaluation of effects of back pressure on the engine.
  ii)  System scalability.
  iii) Sizing, compactness and packaging issues.
  iv)  Regulatory use of $NH_3$ and LiBr as refrigerants and absorbents on vehicles.
  v)   Design of heat exchanger to extract sufficient heat from the exhaust.

vi) Analysis of corrosion effects on the desorber due to exhaust gases and subsequent effects on heat transfer performance.

vii) Refrigeration system performance at low engine speeds.

## 2.2 Modelling work

When compared to experimental research, there are a lot more research articles on modelling, simulation and theoretical aspect of coupling the VARS with the engine exhaust, micro-turbine exhaust and even coupling them with solar panels. Extensive design maps on how to operate the VARS and what conditions are most favourable to attain the highest system efficiency and VARS COP are outlined in these articles. In order to keep literature relevant to the use of VARS on vehicles, only the ones that employ engine exhaust heat are discussed here.

Fernandez-Seara et al [35] designed and modelled a heat recovery system to power an ammonia water based VARS on-board a trawler chiller fishing vessel. The heat recovery system consisted of two heat exchangers. The first one was an exhaust gas to thermal fluid heat exchanger and the second one a thermal fluid to $NH_3$-$H_2O$ solution heat exchanger. The former was made of a finned tube matrix which was arranged in series and fitted to the engine exhaust. The latter heat exchanger acted as the desorber of the VARS and was made of a two-pass kettle type heat exchanger fitted to the bottom of the distillation column. Two heat exchangers were used because the operating temperature of the engine and the VARS were entirely different, the engine operating between 350 $^o$C and 420 $^o$C and the VARS operating between 100 $^o$C and 150 $^o$C. A prototype based on the above designs was built. The remainder of the paper concentrated on modelling of these two heat exchangers and the design of a control system to regulate the flow of exhaust gases through the first heat exchanger which in turn controlled the heat input at the desorber. The entire heat recovery system depended on the operating conditions required at the desorber viz the desorber pressure, temperature and heat load. The paper does not talk about the whole VARS but just the desorber and the heat recovery unit and states that

VARS will be a good fit for the trawler chiller fishing vessel due to constant operation of the trawler engine during fishing periods and low refrigeration needs on-board the trawler.

Talbi and Agnew [19] carried out a theoretical study to combine a turbocharged diesel engine with an absorption refrigeration unit when operating at a high ambient temperature of 35 $^{o}$C. The high ambient temperature condition was chosen because that would place the harshest constraints for operation of the engine. They used a caterpillar diesel engine for their simulation in four different modes – non cooled engine, engine with inter-cooler, engine with pre-cooler and engine with both pre and inter-cooler. The use of an inter-cooler and a pre-cooler on an engine increases its brake thermal efficiency and also the power output when compared to a non-cooled engine. Their idea was to use the chilled water generated from the absorption refrigeration unit to cool the vehicle interior and also the inlet air entering the compressor of the diesel engine. High exhaust temperatures produced a higher amount of cooling in the absorption refrigeration system but at the expense of diesel cycle efficiency. The overall system efficiency of the configuration which had the engine fitted with both the inter-cooler and the pre-cooler was marginally lower than that of the configuration which had the engine with neither the pre-cooler nor the inter-cooler. No details of either the absorption refrigeration system or any of the heat exchangers used in the system were given.

Keinath et al [20] presented a modelling study on coupling a diesel engine with an absorption refrigeration system (with $NH_3 – H_2O$ working pair) to produce chilled water. Their primary focus was to work with a single stage absorption refrigeration system, to optimize the operating conditions and to make it suitable for a small scale system catering to cooling loads up to 2 kW. For the baseline study they achieved a COP of 0.69 for the cooling mode. They suggested controlling the chilled water inlet temperature to the evaporator in order for the system to achieve almost similar COPs over the entire ambient temperature range from -20 $^{o}$C to +49 $^{o}$C for the cooling mode. By employing such a control strategy, the system was able to cater to the required cooling load of 2 kW for the entire ambient temperature range and was able to achieve a higher system COP but at the cost of higher temperature of chilled water. The heat transfer between the exhaust gases and the desorber was achieved via a separate heat transfer fluid; direct coupling between the hot exhaust gases and the

desorber was not done due to temperature incompatibility. No details of the diesel engine used or any of the heat exchangers employed in the absorption refrigeration system were given but a reference to another paper [36] in which these details were listed out was provided.

Three groups [8, 21, 22] carried out theoretical modelling on integration of a VARS specifically for air conditioning on passenger vehicles.

Ramanathan and Gunasekaran [21] used the VAR technology based on $H_2O$-LiBr working pair for the air conditioning application. They focussed on gathering reference data for the scenario when the vehicle was idling because the cooling power of the VARS decreases when the engine is idling (due to reduced thermal energy input). Hence for the VARS to be considered as a replacement for the VC system this data was very crucial. They made use of experimental data of the engine from another research group [17]. The cooling load required for an air conditioning system fitted on a mid-sized passenger vehicle is about 2 kW at both idle and cruise conditions. Fin and tube type heat exchangers were used for the evaporator, condenser and the absorber and plate and tube heat exchangers were used for the desorber and the solution heat exchanger. A direct heat recovery mode where the engine exhaust was directly coupled to the desorber of the VARS was employed. From their simulation studies they found that at an idling RPM of 1300, the evaporator capacity was about 3.7 kW and this increased to 11 kW when the RPM was increased to 2000. This was attributed to the increased heat input into the desorber due to increased mass flow rate of the exhaust.

Vicatos et al [22] carried out a theoretical analysis of an air conditioning system for a Nissan 1400 mini truck powered by engine exhaust. They also verified their theoretical analysis with a laboratory prototype and concluded that a lot of improvements had to be made to their overall design due to the low COP values achieved, in the order of 0.08. The VARS unit used for the air conditioning system was based on an $NH_3$-$H_2O$ working pair but taking into account the toxicity of $NH_3$, a direct expansion evaporator was not used but rather a secondary fluid (water glycol mixture) was used to cool the passenger space. Their designed system generated a cooling load of 2 kW at 0 $^o$C which was more than sufficient to cater to the needs of the vehicle chosen.

Javani et al [8] carried out a thermodynamic analysis, by performing an energy and exergy analysis, of waste heat recovery for cooling systems (mainly air conditioning for cabin) in hybrid and electric vehicles. They analysed two refrigeration cycles, the ejector cycle and the absorption cycle for cabin cooling in hybrid electric vehicles (HEVs) and electric vehicles (EVs). Only the results from the absorption cycle will be discussed here in order to keep literature relevant. In HEVs, the heat for running the refrigeration system was obtained from the exhaust gases whereas in EVs the heat was obtained from the cooling loop used for thermal management of the battery. A thermal coupling fluid was used to extract heat from the exhaust gases and transfer it to the desorber rather than directly couple the desorber to the engine exhaust. The amount of heat dissipated through the exhaust for different vehicles is given in Table 3 [7]. The thermodynamic analysis was carried out for a mid-sized vehicle (average wheelbase 2700 mm and average interior volume 3.2 $m^3$).

Table 3: Heat recovered through exhaust (kW) for different vehicles

| Vehicle type driving mode | Subcompact | Compact | Mid-size |
|---|---|---|---|
| Highway driving | 14.6 | 20.3 | 29.2 |
| City driving | 9.1 | 12.2 | 18.2 |

(tentative figures)

They found that in EVs, the cooling loop does not provide sufficient input thermal energy to the absorption system for achieving the desired cooling load required for air conditioning, the cooling achieved at the evaporator being around 2 kW. In comparison to EVs, the cooling achieved in HEV's at the evaporator was about 7.9 kW which is more than sufficient to cater to the needs of air conditioning on the vehicle. The heat recoverable from the exhaust gases in the HEV was around 15 kW and this meant a COP of 0.52 could be achieved. Besides conducting a thermodynamic study, the authors did not specify any information on either the diesel engine used or the kind of heat exchangers employed in the absorption cooling system.

Sarabchi et al [37] carried out simulation studies for coupling a Homogenous Charge Compression Ignition (HCCI) engine with an Ammonia-Water Cogeneration Cycle (AWCC) which is basically a combination of the Rankine cycle and absorption refrigeration cycle, thereby providing both power and cooling. The exhaust gas from the HCCI engine was directly fed to the desorber of the AWCC

after passing through a series of heat exchangers, resulting in desorber temperatures between 130 $^{\circ}$C and 180$^{\circ}$ C. They found that the cooling capacity had an inverted 'U' shape, with a maximum value at a particular pressure ratio (desorber pressure/ absorber pressure) and desorber temperature. Their study was mainly focussed on showcasing the feasibility of the concept and exergy analysis of the whole system. They found that maximum exergy destruction occurred in the engine itself and the absorber of the AWCC.

Another modelling work in the same field by Alam [38] incorporated use of a three fluid VARS coupled to the engine exhaust for air conditioning on a passenger vehicle. The amount of heat available at the desorber depended on the percentage of valve opening between the exhaust gas and the desorber and sufficient thermal energy was available to cater to the air conditioning needs of the vehicle. Geometric and design specifications of the components were not given however some information on where the components can be packaged was stated. Ouadha and El-Gotni [39] carried out a thermodynamic analysis of the VARS coupled to the exhaust of a marine diesel engine and concluded that system COP increased with high desorber and evaporator temperature and low condenser and absorber temperature. Two papers by Mostafavi and Agnew [14, 40] discussed the thermodynamic aspects of coupling a supercharged diesel engine (with intercooling) and a naturally aspirated diesel engine with the absorption refrigeration unit. Their conclusion was for a supercharged engine, the degree of intercooling affected the integration of the VARS on the vehicle because the exhaust temperature was reduced due to intercooling and there might not be sufficient thermal power to drive the VARS. For a naturally aspirated engine there was sufficient thermal power in the exhaust gases and the cooling capacity depended on the pressure ratio and cycle temperature ratio of the engine.

Few other papers talk about coupling of engine exhaust with adsorption refrigeration systems [7, 41, 42] but adsorption systems as mentioned earlier are bulkier than absorption systems and hence are not considered as a viable alternative to VC systems.

As we can see, research on the modelling aspect of coupling the engine exhaust with VARS is not entirely focussed on one particular area but is instead spread over to different areas, ranging from studying the performance of the diesel engine, to control of VARS and also the operational characteristics for the VARS. Most of the modelling studies focussed on passenger vehicles and not on heavy duty trucks and in all the models only a system level '0D' model was presented. In order to consider VARS as a replacement for VC units, detailed component level modelling along with system level modelling is required in order to assess the component's ability to perform according to design specifications. Also as Boatto [17, 29] mentioned, each and every component must be designed and developed separately for a particular class of vehicles due to space constraints.

A time line representing the experimental and modelling research carried out till date is presented in Figure 4 and Figure 5 and a summary of the research work carried out for coupling of the VARS with the engine exhaust is given in Table 4.
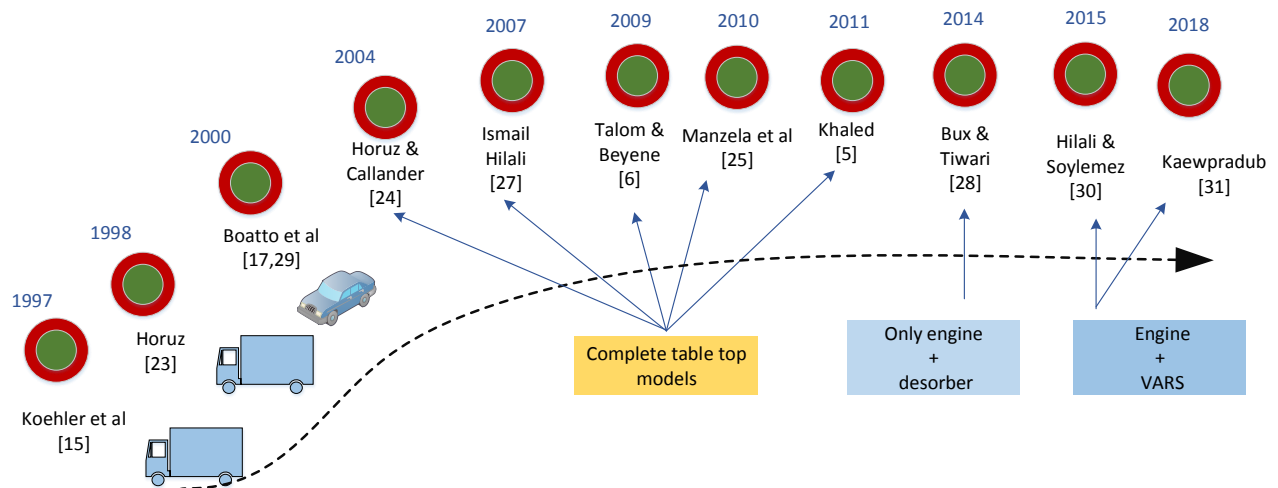


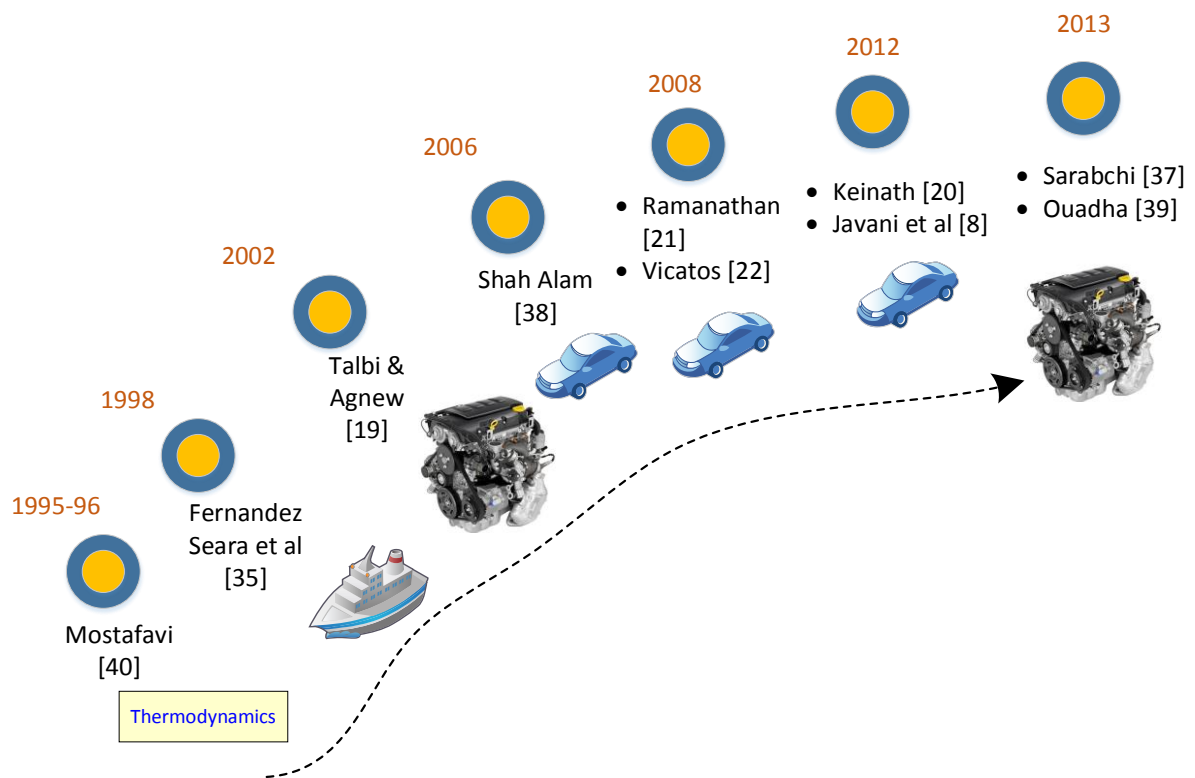Figure 4: Timeline showing experimental research on VARS coupled to engine exhaust

Figure 5: Timeline showing modelling research on VARS coupled to engine exhaust

Table 4: Summary of research activities carried out on coupling of engine exhaust with absorption refrigeration

| Research group | Nature of work | Working pair | VARS unit details/ Application | Main focus points | Practical application on vehicle | Type of vehicle focused |
|---|---|---|---|---|---|---|
| Koehler et al [15] | Experimental | $NH_3$-$H_2O$ | Complete unit / Refrigeration | Design of VARS components, coupling of engine exhaust with VARS, performance of VARS | Yes | Trucks |
| Horuz [23] Horuz & Callander [24] | Experimental | $NH_3$-$H_2O$ | Complete unit/ Refrigeration | Integration of engine and VARS, effect on engine performance due to coupling with VARS | No | Trucks |
| Manzela et al [25] | Experimental | $NH_3$-$H_2O$ | Complete unit / Refrigeration | Experimental integration of engine with commercially available VARS | No | Not specified |
| Khaled [26] | Experimental | $NH_3$-$H_2O$ | Only desorber / air conditioning | Desorber design for automobile air conditioning | No | Not specified |
| Khaled et al [5] | Experimental | $NH_3$-$H_2O$ | Complete unit / air conditioning | Prototype construction and study, Linkage of COP to other parameters | No | Not specified |
| Ismail Hilali [27] | Experimental | $H_2O$-LiBr | Complete unit/ air conditioning | Design of VARS components, coupling of engine exhaust with VARS, performance of VARS | Yes* | Trucks |
| Talom and Beyene [6] | Experimental | $NH_3$-$H_2O$ | Complete unit / refrigeration or air conditioning | Integration of engine and VARS and system operation at part load and full load conditions | No | Not specified |
| Bux & Tiwari [28] | Experimental | $H_2O$-LiBr | Only desorber unit / air conditioning | Integration of diesel engine with plate heat exchanger desorber, engine performance study | No | Not specified |
| Boatto et al [17, 29] | Experimental | $H_2O$-LiBr | Complete unit / air conditioning | Engine performance characteristics, component layout on the vehicle | Yes | Passenger vehicle |
| Aly et al [32] | Experimental | $NH_3$-$H_2O$ | Diffusion Absorption Refrigerator (DAR) | Evaluate domestic DAR's performance when coupled to engine exhaust, study engine operating characteristics, control | No | Not specified |
| Rego et al [33] | Experimental | $NH_3$-$H_2O$ | Diffusion Absorption Refrigerator (DAR) | Coupling of engine exhaust with desorber, control of exhaust gas flow | No | Not specified |

| Lin et al [34] | Experimental | $NH_3$-$H_2O$ | Diffusion Absorption Refrigerator (DAR) | Performance of DAR when coupled to engine exhaust | No | Not specified |
|---|---|---|---|---|---|---|
| Fernandez-Seara et al [35] | Modelling | $NH_3$-$H_2O$ | Only desorber / Refrigeration | Heat recovery and desorber integration with trawler engine | No | Fishing trawlers |
| Talbi and Agnew [19] | Modelling | Not specified | Complete unit / Refrigeration | Heat recovery, availability of heat for VARS and also for engine pre-cooler and inter-cooler | No | Not specified |
| Keinath et al [20] | Modelling | $NH_3$-$H_2O$ | Complete unit / air conditioning | Optimising operating conditions of the VARS, design of control system and modelling for small scale 2 kW cooling system | No | Not specified |
| Ramanathan and Gunasekaran [21] | Simulation | LiBr-$H_2O$ | Complete unit / air conditioning | Use of engine exhaust heat to power VARS, specific consideration during engine idling | No | Mid-sized passenger car |
| Vicatos et al [22] | Theoretical analysis | $NH_3$-$H_2O$ | Complete unit / air conditioning | Theoretical design of VARS components for automobile air conditioning system, verification of theoretical design with laboratory and road tests | Yes[#] | Mini truck |
| Javani et al [8] | Thermodynamic analysis | LiBr-$H_2O$ | Complete unit / air conditioning | Air conditioning system based on VARS, comparison of thermal energy transfer from engine exhaust and cooling fluid used for battery cooling | No | Hybrid electric vehicles and pure electric vehicles |
| Sarabchi et al [37] | Modelling | $NH_3$-$H_2O$ | Complete unit / Refrigeration | Coupling of Homogenous Charge Compression Ignition engine with AWCC, Exergy analysis | No | Not specified |
| Shah Alam [38] | Modelling | $NH_3$-$H_2O$ | Complete unit / air conditioning | Integration of engine exhaust with three fluid vapour absorption system, availability of heat with throttle valve opening | No | Cars |

| Ouadha and El-Gotni [39] | Thermodynamic study | $NH_3-H_2O$ | Complete unit / refrigeration and air conditioning | Integration of marine diesel engine with VARS, performance characteristics of VARS | No | Not specified |
| Mostafavi [14, 40] | Thermodynamic analysis | Not specified | Complete unit / air conditioning | Thermodynamic analysis of supercharged and naturally aspirated diesel engine with VARS, engine performance maps | No | Not specified |

*Intended for truck applications but installation on truck not carried out; # laboratory prototype developed

## 2.3 Discussion and analysis

From all these studies, it is clear that the amount of thermal energy available from the engine exhaust is more than sufficient to cater to the cooling load requirements but only when the vehicle is cruising (above a certain speed) or in other words between a certain minimum and maximum engine RPM (of that particular engine). In the idling scenario, the engine exhaust flow rate is low which results in insufficient heat input delivered to the VARS and a need for a back-up burner arises. Also, the engine performance is greatly affected by coupling of the VARS to its exhaust; the back pressure generated at the engine exhaust has a negative effect on the engine performance. Another problem is the temperature incompatibility between the exhaust gas and the desorber and the corrosion effects on the desorber due to exhaust temperature.

Hence, linking the absorption refrigeration unit with the internal combustion engine has its own set of problems. Every engine has a particular efficiency map and the highest efficiency is achieved at a particular rpm. Operation at rpms and torque levels outside this range will result in poor engine efficiency and increased fuel consumption. The absorption refrigeration system does not perform that well when the engine is idling and this might hinder the usage of thermally driven VARS for refrigerated trucks and automobile air conditioning.

From the literature review, it is clear that if the VARS is to be used for air conditioning then $H_2O$-LiBr is the preferred working fluid else if it is to be used for refrigeration then $NH_3$-$H_2O$ is the working fluid to be employed. This is because sub-zero temperatures cannot be achieved when water is used as the refrigerant. Secondly, in many of the studies presented above, the coupling between the engine exhaust and the desorber is achieved via a separate fluid which then delivers the required heat to the desorber at the right temperature. This mode of coupling will accomplish two things, one reduce the back pressure effects on the engine and second prevent corrosive effects of exhaust on the desorber. The use of an intermediate coupling fluid will result in additional components like pump and storage tank on the vehicle but the trade-off lies in better engine performance.

The throttle valve or the baffle position between the exhaust and the desorber plays a major role in the performance of the VARS. Most of the research papers recommend controlling the valve position in order to control the heat input to the desorber. The authors who have worked on the control aspect have claimed that implementation of the VARS without a control mechanism (for heat input) will result in poor performance of the VARS.

Koehler et al [15] made an assessment on the kind of terrain that will be best suited for a truck fitted with a VARS and concluded that it works best when driving on flat roads for long distances. This is because the engine RPM stays almost constant and the amount of heat supplied at the desorber also stays constant, thereby achieving a constant performance from the VARS. In city conditions as the engine has to idle frequently, the amount of heat delivered to the desorber is either insufficient or is intermittent in nature which in turn affects the performance of the VARS. In mountainous terrain, once again the exhaust temperature varies a lot which affects the desorber performance and in turn the performance of the VARS as a whole. Hence, using engine exhaust heat to drive the VARS without back-up burners and adequate control mechanism can be quite challenging and unreliable.

Experimental research on prototype development of compact VARS for trucks has been virtually stagnant after 1998 as seen from Figure 4. Bespoke design and development stopped with Ismail Hilali's PhD thesis [27] and after that the research groups have just coupled commercially available products and evaluated their performance for suitability for implementation on automobiles. Hence individual component design, modelling and development for different types of vehicles for both air conditioning and refrigeration applications is the way forward to qualify VARS as a replacement for VC units in areas where residual thermal energy is available.

## 3 Absorption refrigeration systems coupled to Fuel Cells

Fuel Cells are devices that electrochemically convert chemical energy of fuel to generate both electricity and heat. In high temperature fuel cells, the heat generated is of high quality and by quality it means the amount of useful work that can be gleaned out of it is high. Heat generated as a by-product from fuel cells can be used as the driving force to operate VARS in a CCP (Combined

Cooling and Power) and a CHCP (Combined Heating Cooling and Power) mode and this idea has been explored by many research groups. A summary of the activities carried out by different research groups in this field is outlined in this section. The literature on coupling of fuel cells with VARS is important from the point of view to see if there are any key technological takeaways or loop holes that need to be addressed when adapting fuel cell heat driven VAR technology to vehicles.

Zink et al [43] combined an SOFC system with a VARS based on $H_2O$-LiBr working pair for providing heating, cooling and hot water for buildings. Their work mainly focussed on the modelling and simulation aspect of the whole system and comprised of three parts - an internal reformer model, an SOFC model and an absorption chiller model. They chose internal reforming over external reforming due to the fact that the former has higher efficiencies and faster load responses when compared to the latter. The SOFC model developed was based on a pre-commercial 110 kW tubular SOFC stack developed by Siemens-Westinghouse and the VARS model developed was based on a commercial $H_2O$-LiBr gas fired VARS unit available from Dalian Sanyo Refrigeration Co. Ltd. All three models were developed and implemented using the FORTRAN software package and the system architecture developed is shown in Figure 6. In the system architecture developed, the exhaust from the after-burner unit (combustor) was used as the heat source in the desorber of the VARS. Their model had the capability to cater to the needs of space heating, cooling and providing hot water to a building of 9500 $m^2$ floor space and had an overall efficiency of 87% if both electricity and heat from the SOFC were utilised. They also stated that conventional VC systems are highly efficient when considered as a standalone unit however thermally driven refrigeration systems when combined with a fuel cell offer a higher overall system efficiency. They concluded that the combined system as a whole was technically feasible, however economic considerations might hinder implementation practically.
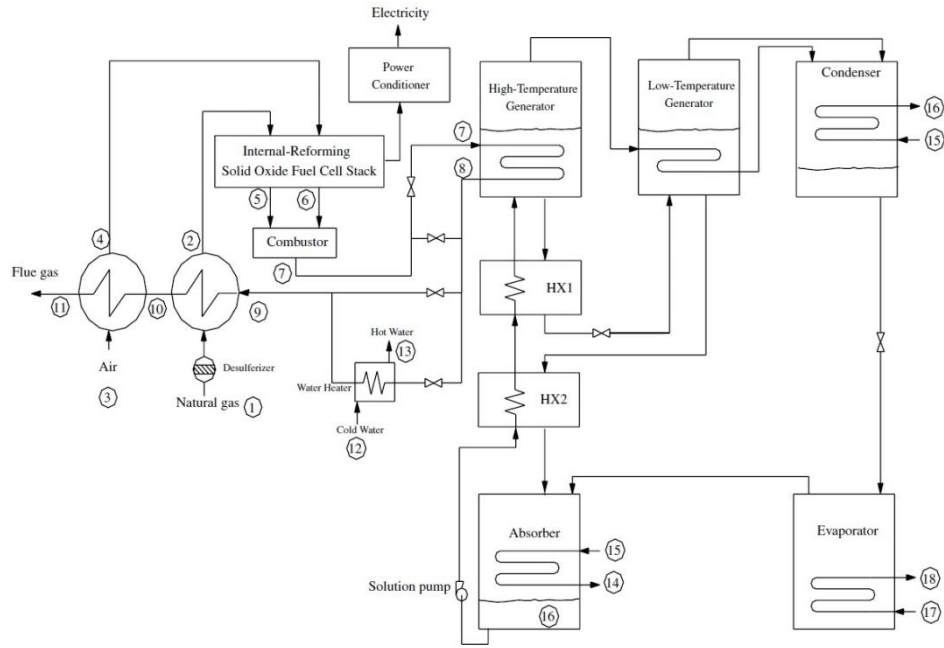
Figure 6: Combined SOFC-VAR architecture developed by Zink et al [43]

Oshima et al [44] carried out a study on recovering FC exhaust to power a cooling system meant for telecommunication equipment. Their main focus was to look into different methods of heat recovery from the fuel cell and draw appropriate conclusions on which heat recovery system was better. The fuel cell used by them was a Phosphoric Acid Fuel Cell (PAFC) and they studied two different heat recovery methods - *mixed type heat recovery* method and *separate type heat recovery* method. The mixed heat recovery method involved combining the exhaust from the reformer and the cathode side of the PAFC and using the combined mixture in a heat exchanger to deliver the required quantity of heat to water which was then used as the coupling fluid in the desorber of the VARS. In the separate heat recovery method, the exhaust from the reformer and the cathode were used in separate heat exchangers to heat water and the heated water from these two separate heat exchangers was combined and then used in the desorber of the VARS. The total amount of heat recovered from the exhaust gases was calculated using sensible heat of the exhaust gas along with latent heat and sensible heat of the water vapour present. In both methods, the amount of heat recovered increased with decrease in exhaust gas temperature but the difference lay in the temperature of condensation of water vapour. The separate type heat recovery method had a higher temperature of condensation of water vapour due to increased partial pressure of water vapour. The reason for this was because the partial pressure

of water vapour in the exhaust from the reformer was much higher than that in the exhaust from the cathode or for that matter in the combined reformer-cathode stream. So effectively a greater quantity of heat could be recovered at a higher temperature in the separate type heat recovery method. Based on the heat recovery data, the cooling capacity of the absorption refrigerator that used a separate type heat recovery method, at a source temperature between 65 and 85 $^{o}$C, was about 2.5 times greater than the cooling capacity of the absorption refrigerator that used a fixed temperature heat source at 85 $^{o}$C. No detailed information was provided by the authors on the type of absorption refrigerator or the components used in it.

Zeting Yu [45] developed a steady state mathematical model to simulate a TES (Total Energy System) comprising an SOFC and an absorption chiller in order to provide cooling, heating and power. The schematic developed by them for the total system is shown in Figure 7 and is akin to the system developed by Zink et al [43].
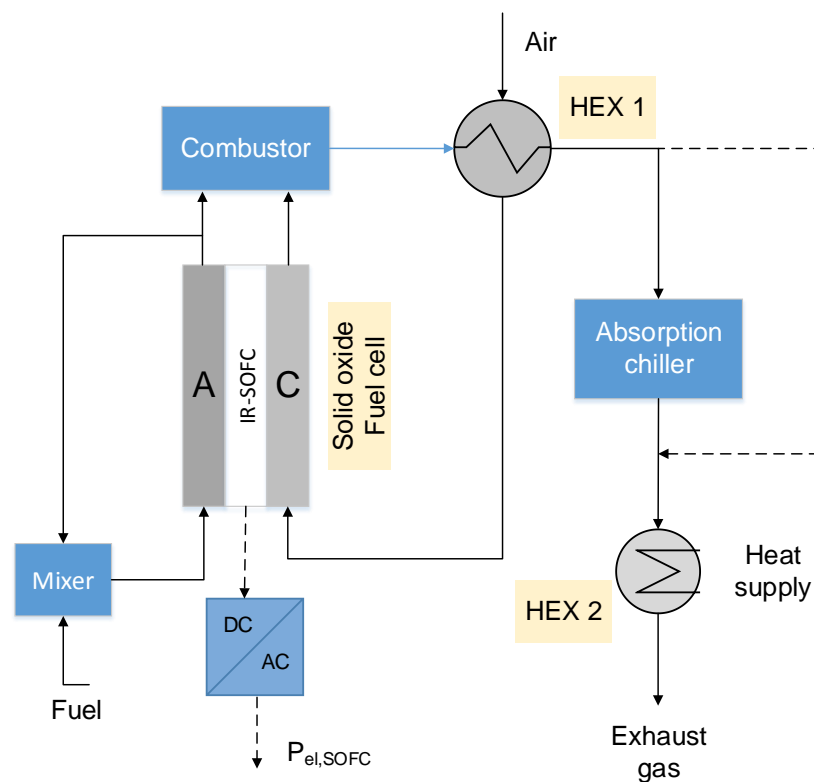


Figure 7: Schematic of TES comprising SOFC and absorption chiller [45]

The mathematical model, developed in MatLab simulates the performance of the TES and the SOFC under different operating conditions. Internal reforming was chosen over external reforming for the SOFC model because it has a higher efficiency and a faster load response. They validated their SOFC model with the data available for a tubular SOFC from Siemens Westinghouse. The developed model provided flexibility in varying certain operational parameters such as anode gas recirculation ratio, average current density, fuel utilization and SOFC cathode inlet gas temperature, however the results presented discussed the effects of only current density and fuel utilisation. With increase in current density more heat is generated within the fuel cell and hence more heat has to be removed from it. This results in an increase in temperature of the exhaust stream and in turn increased heat input to the desorber of the VARS. Increased heat input to the desorber also results in increased cooling output and thus increased cooling efficiency. However, the electrical efficiency of the fuel cell is reduced and this when combined with the cooling efficiency, reduces the total efficiency of the system. With an increase in fuel utilisation of the fuel cell, electrical efficiency and the total efficiency increase but the cooling efficiency decreases. This is because higher fuel utilisation results in lower combustion temperatures which lead to reduced heat input to the desorber and in turn reduced cooling output. A limit of 0.85 for the fuel utilisation was established beyond which the electrical efficiency did not increase but rather decreased.

As seen from the findings of Zeting Yu [45], the electrical efficiency and cooling efficiency behaved in a totally opposite manner when current density and fuel utilisation were varied. Hence a trade-off needs to be made between these two operational parameters of the SOFC depending on the application required. Once again no details were given about the absorption refrigeration unit or any of the heat exchangers used.

Another paper published by Zeting Yu et al [46] talks about a tri-generation system comprising an SOFC and a double stage absorption chiller, to provide combined cooling, heating and power. Their combined system could produce an electrical power of 339 kW along with 303.6 kW of cooling and 267 kW of heating, consuming about 40.2 g s$^{-1}$ of fuel and 672 g s$^{-1}$ of air. The fuel for the SOFC was derived from a gasification process and hence had to be internally reformed. Through their

simulations they showed that a CCP (Combined Cooling and Power) efficiency of 89 % and a CHP (Combined Heating and Power) efficiency of 84 % can be achieved. Similar to their previous paper, this paper also talks about the effect of different SOFC parameters on the performance of the whole system. The coupling between the SOFC stack and the absorption chiller was achieved via HRSG (Heat Recovery Steam Generator) where saturated steam was generated and was used to drive the high temperature desorber of the double stage VAR unit.

Darwish [47] proposed using a Phosphoric Acid Fuel Cell (PAFC) in combination with both VC system and VARS unit, to cater to air conditioning needs of buildings in Kuwait. They also proposed having a cold storage system as a buffer so that air conditioning needs during peak times can be met however stated that there is no current expertise in the field of cold storage systems in Kuwait and hence the air conditioning needs had to be met by the VC and the VAR unit working together. This kind of integrated system was proposed to reduce the dependence on grid electricity for large buildings and instead employ small distributed generation units for each building. The PAFC chosen was a commercially available ONSI P24 with a nominal capacity of 200 $kW_e$. This came with a standard heat exchanger in the BoP (Balance of Plant) capable of supplying hot water at a temperature of 70 $^{o}$C1  To integrate the VARS with the system, another high temperature heat exchanger had to be added to the system architecture. The chosen VC system had a maximum cooling capacity of 500 kW and the VARS unit had a maximum cooling capacity of 73.5 kW, hence put together they were able to cater to a cooling load of 573.5 kW. For the reference building of 1557 $m^2$, the maximum cooling load required during the hottest month of the year and during the hottest time of the day was around 569.5 kW. Hence the integrated PAFC-VC-VAR system was able to cater to the maximum cooling load at any time.

Waragai et al [48] studied the characteristics of an absorption refrigerator driven by PAFC exhaust heat. The application of the absorption refrigerator was specifically for telecommunication equipment cooling which required a cooling system working continuously. Two different ways of heat recovery from the PAFC stack were proposed. One from the exhaust gases of the PAFC and the second from the coolant that is circulated through the stack. If the stack is operated at a specific rating then the

amount of heat recovered from the coolant stays constant. In recovering heat from PAFC's exhaust gases, the temperature at which water condenses played a crucial part because the heat recovery from the exhaust gases depended on the water recovery temperature. A brief discussion of this was presented above in Oshima et al's work [44]. The VARS employed was a combination of single stage and double stage configurations (based on $H_2O$-LiBr working pair) where a high temperature desorber and a low temperature desorber were employed and a working prototype was built. Steam generated by recovering heat from the coolant was supplied to the high temperature desorber (~ 160 $^{o}$C) and hot water generated by recovering heat from the PAFC's exhaust gases was supplied to the low temperature desorber (65-85 $^{o}$C).

For year round operation of the VARS, the cooling water temperature at the absorber and condenser was set to 15 $^{o}$C. This value was derived considering the effect that cooling water has on both COP and the concentration of solution. Reduction in cooling water temperature increased the COP but decreased the concentration of the solution. Also, from the design map it was found that a low temperature heat source could be used for the VARS if the cooling water temperature was reduced. The other parameters affected by cooling water temperature were cooling performance, desorber/condenser pressure and absorber/evaporator pressure. Cooling performance increases whereas desorber and absorber pressure decreases with decrease in cooling water temperature.

They also tested the absorption refrigerator in two modes. The first where only steam was used as the heat source in the desorber and second where both steam and hot water were used as heat source. Operation in both modes was successful, the only difference being in the amount of cooling generated, the latter generating more cooling than former due to the use of two heat sources (50 kW from former and 65 kW from latter). Also, the COP was around 1.5 for the double stage cycle and just 0.5 for a single stage cycle. The hot water used in the low temperature desorber was heated by the fuel cell's exhaust stream. Technically, its temperature should depend only on the quantity of heat that the fuel cell exhaust can transfer but in reality the cooling water temperature used in the VARS also affected the temperature of the hot water. A decrease in the cooling water temperature decreased the temperature of the hot water and in turn the heat transfer capacity to the low temperature desorber. It

was concluded that it was best to operate the VARS unit as a double stage unit with both steam and hot water as heat sources. This increased the cooling performance by 50% when compared to a single stage single heat source VARS unit.

Ishizawa et al [49] also integrated a 200 kW PAFC with an absorption chiller to provide electricity for powering telecommunication equipment and to cool the room where it was kept. They tested the combined system in the field at two locations - NTT Yokohama branch and NTT Kansai centre in Japan. The main focus of their study was recovery of heat in the temperature range of 80-85 $^{o}$C from FC exhaust gases using suitable heat exchangers and also recovery of water from the exhaust gases in order to supply water to the cooling system of the PAFC. For heat recovery from the PAFC exhaust gases they employed a shell and tube heat exchanger (the coupling fluid being water) and for water recovery from the exhaust gases they used a DCC (Direct Contact Cooler). They employed a double stage absorption chiller and guessing by the application it is believed that $H_2O$-LiBr working pair was used. The heat recovered from the PAFC coolant was transferred to the high temperature desorber and the heat recovered from the exhaust gases (through the coupling fluid) was transferred to the low temperature desorber. Recovery of heat from the FC exhaust gases was critical during winter time because a higher input temperature was needed at the low temperature desorber.

They concluded that the amount of heat recovered from the PAFC exhaust gases and the amount of water condensed from the exhaust gases increased if the inlet temperature of the water supplied at the shell and tube heat exchanger was reduced and this in turn depended on the ambient temperature where the cooling towers of the absorption chiller were placed. On the whole they were able to achieve a heat recovery between 26 and 38 % combined, from both the PAFC coolant and the PAFC exhaust gases and were able to operate the absorption chiller all year round even during peak summer.

Sevencan et al [50] carried out an economic study on the use of an MCFC coupled with VARS for data centre cooling and concluded that the system was not economically feasible due to high capital and Operational & Maintenance (OM) costs and also that the lifetime of the current MCFC stacks was

too short. This was a pure economical study and no technical details, besides the type of the MCFC (DFC300 from Fuel Cell Energy), were provided.

Yang et al [51] modelled a hybrid system that comprised a PAFC and an absorption refrigerator and mapped out general performance characteristics and optimum design criteria for the hybrid system. The power density from the hybrid system reached its maximum at a higher current density than the individual systems. In addition, the hybrid system's power density was higher than the individual PAFC system's power density by 2.6 % which implied that it was better to operate the PAFC in a hybrid configuration rather than as a standalone fuel cell unit. In the above context, they defined power density as the amount of power produced per bi-polar plate area of the fuel cell. The power was pure electrical if the PAFC alone was operated and was a combination of electrical and thermal if the PAFC was operated in a hybrid mode. They also identified a critical minimum current density of 0.05 A cm$^{-2}$ for the PAFC above which the absorption refrigerator started to cool the refrigerated space and a maximum current density of 0.88 A cm$^{-2}$ above which the power density of the hybrid system began to drop. The efficiency of the hybrid system decreased continuously with current density although for the entire current density range it was higher than the individual PAFC unit. Besides specifying the current density, parametric studies were carried out for the operation of hybrid system with variations in operating and functional parameters of the PAFC such as temperature, pressure, thermodynamic losses and phosphoric acid concentration. They concluded that temperature and pressure of the PAFC had the highest influence on the operation of the hybrid system. No details on PAFC sizing, the method of heat recovery, thermal coupling with the absorption refrigerator or the components of the absorption refrigerator were provided.

Weber et al [52] focussed on decentralized energy generation for buildings in Tokyo, Japan using an SOFC and coupling it to an absorption chiller for providing cooling/heating for buildings. They chose a double stage absorption chiller based on $H_2O$-LiBr working pair because the main purpose of the absorption chiller was to provide air conditioning and not refrigeration. The absorption chiller was powered by the exhaust gas coming from the combustor employed in the SOFC BoP (Balance of Plant). Their main findings were that a 30% reduction in $CO_2$ emissions could be achieved when

employing an SOFC-VARS system when compared to the conventional case but with a cost increase of almost 70%. They also found that a completely decentralised system with a VARS alone was not possible and an electric chiller needed to be incorporated to cater to the deficiency in cooling/heating load because the sized SOFC for the building could not supply enough exhaust gas to the absorption chiller.

Margalef and Samuelsen [53] integrated an MCFC (Molten Carbonate Fuel Cell) with an absorption chiller for a commercial building and stated that a high value market exists for such hybrid configurations in the distributed generation and CCHP (Combined Cooling Heating and Power) market. They modelled the MCFC based on the data available from a commercially available product, *DFC300MA* manufactured by *FuelCell Energy* and also a commercially available absorption chiller from *Yazaki CH4040-KE*. Their integrated system could produce 300 kW of electrical power and 40 ton (140.7 kW) of refrigeration. The desorber in the refrigeration unit utilised the high temperature exhaust from the MCFC but also had provisions for another high temperature desorber, which combusted natural gas in case the thermal energy supplied by the MCFC exhaust was not sufficient. The VARS had a dual fired desorber, powered by exhaust and natural gas burner and employed $H_2O$-LiBr as the working pair. They identified two critical issues that might pose problems when integrating the two systems. One issue was the '*cold end corrosion*' when acid and water vapour in the hot flue gases coming from the combustor of the fuel cell BoP might condense on the cooler end of the desorber of the absorption chiller and lead to its corrosion and eventually its failure. The second issue was the crystallisation of the LiBr solution when the mass fraction of LiBr exceeded its solubility limit in water. In order to cater to the above issues, they employed the following three strategies to integrate the MCFC exhaust with the absorption chiller. The first strategy was to use the MCFC exhaust directly, the second was to blend it with ambient air at 25 $^o$C, and the third was to blend it with the chiller exhaust gas (which is approximately 120 $^o$C). Their main findings were that although the first strategy produced satisfactory results it was better not to employ it because in this case, the MCFC exhaust was used directly as the heat source and there might be some temperature mismatch (between the fuel cell and VARS), leading to ineffective operation of the absorption chiller.

Also, the absorption chiller manufacturer did not recommend using the MCFC exhaust at such high temperatures directly. In the second strategy, the exhaust mass flow rate was increased but the temperature of the exhaust was reduced due to mixing of air at 25 $^o$C. This affected the chiller performance nevertheless it was still higher than the first strategy. The last strategy was the best amongst the three because blending the MCFC exhaust with the chiller exhaust not only increased the mass flow rate but also did not allow the exhaust temperature to drop too much which led to increased chiller performance.

Arsalis [54] carried out modelling and simulation studies to integrate a 100 kWe HT-PEFC (with cell active area of 605 cm$^2$) subsystem with an absorption chiller for a commercial ship/container vessel. They employed a special thermal oil to cool the HT-PEFC stack and routed this to the desorber section of the VARS. A total of 107 kW of heat could be recovered from the fuel cell. They modelled two kinds of absorption chiller for system integration - a double stage type with $H_2O$-LiBr as the working pair and a single stage type with $NH_3$-$H_2O$ as the working pair. The former could satisfy a cooling load requirement of 128.2 kW and the latter a cooling load requirement of 64.5 kW. Their proposed design was very simple where the coolant from the fuel cell was circulated to the desorber of the VARS and then back to the fuel cell. No specifics were given on the heat exchangers/ equipment used between the HT-PEFC and the VARS.

Pilatowsky et al [55] carried out simulation studies to work out the optimum operating conditions needed to run an air conditioning system based on an absorption refrigeration cycle using heat from a PEFC. The working pair employed in the absorption refrigeration cycle was monomethlyamine-water (MMA-WS). They found that COP values rose with increase in desorber temperature, reached a maximum and then dropped with further increase in desorber temperature. This trend in COP variation was replicated for different evaporator temperatures as well. The highest COP that could be achieved was 0.57 at a desorber temperature of 60 $^o$C and an evaporator temperature of 10 $^o$C and the lowest COP was 0.23 at a desorber temperature of 80 $^o$C and evaporator temperature of -10 $^o$C. It was also found that COP of the VARS decreased with increase in electrical power of the PEFC although cooling power increased with increase in electrical power. With 1500 W of electrical power produced

from the PEFC stack, 536 W of cooling could be generated when the desorber temperature was 60 $^{o}$C and 401 W of cooling could be generated when the desorber temperature was 80 $^{o}$C. In order to operate the VARS with a high COP, desorber temperatures between 60 and 65 $^{o}$C and evaporator temperatures between 5 and 10 $^{o}$C were recommended. Evaporator temperatures in this range are quite sufficient for air conditioning purposes. Although not specified explicitly it could be inferred from their block diagram that the thermal coupling between the PEFC and the VAR unit was achieved via a thermal storage tank, the heat being supplied by the coolant used in the PEFC and the hot water generated as a result was used as the heat transfer fluid in the desorber. Details or sizes of the heat exchangers employed in the system were not specified.

A peculiar aspect of their design with regard to the absorption chiller was that the temperature needed for driving the desorber was in the range 60-80 $^{o}$C. This could be attributed to the different refrigerant-absorbent working pair used in the VARS. The fact that the coolant of the PEFC was used as the heat source to generate hot water which in turn was used in the desorber of the VARS raises some questions on the effective temperature levels and heat exchange capabilities of the heat exchanger because the coolant temperature usually is not greater than the operating temperature of the fuel cell.

Frimodt and Mygind [56] studied '*Integration of Solid Oxide Fuel Cells and Absorption Cooling Units*'. They first carried out a market study for implementing such a system and narrowed down on two areas where it can be effectively used viz. APUs for ships (providing both power and cooling) and distributed generation units for hotels. Among the two applications they chose the latter. They developed a thermodynamic model for the whole system using Engineering Equation Solver and the absorption unit was designed as a double stage chiller with $H_2O$-LiBr as the working pair. All components were modelled as black boxes or as '0D' models where the energy and mass flows entering and leaving the system were identified. They also found that the SOFC-VARS unit was able to run effectively in very hot climates only if the humidity was low (dry climates). If the humidity was very high then the system was not able to run effectively at high ambient temperatures, the ambient temperature being restricted to 33 $^{o}$C. They also found a relation between the desorber temperature

and ambient temperature. If the ambient temperature was below 20 $^{o}$C then temperature at the desorber could be restricted to 150 $^{o}$C and a dry cooling tower can be employed. If the ambient temperature exceeded 20 $^{o}$C then either a wet cooling tower was necessary or the desorber temperature had to be increased to 190 $^{o}$C. A final statement was that a complete market and economic study was essential to implement an SOFC-VARS unit at any place.

Another piece of research on modelling and simulation of a high temperature fuel cell with an absorption chiller was carried out by Sarah Marie Martz [57]. Once again, the combined system was designed to cater to the cooling and electrical load requirements of a commercial/institutional building. The fuel cell used was an MCFC and the absorption chiller modelled was based on the H$_2$O-LiBr working pair. A steady state and a dynamic model of the absorption chiller were established. Aspen Plus was used as a platform for carrying out the steady state simulations and Matlab/Simulink was used as a platform for carrying out dynamic simulations. No modelling of the MCFC was carried out but a detailed system integration strategy with the building and a thermal load following model was designed.

Mehrpooya et al and Zhao et al [58, 59] focussed on integration of SOFC-CHP systems into existing power plants to increase the overall efficiency of the power plant and at the same time also cater to the cooling and heating needs of the power plant. In the former, a combined SOFC gas turbine power plant-VARS-Rankine cycle was analysed both from an energy and exergy point of view and the optimal design conditions were established by carrying out a sensitivity analysis by varying key variables of the system. An economic study was also carried out for optimal design of the whole process. More emphasis was placed on the process itself rather than individual component design. In the latter, an SOFC-VARS system was integrated with a coke generating power plant whose residual fuel COG (Coke Oven Gas) was reformed and used in the SOFC. Once again, the performance criteria and the main factors influencing system performances were chartered out. Both these papers provided insights into power plant design and system evaluation but gave out very little information on the kind of heat exchangers used for the VARS.

Takezawa et al [60] proposed SOFC assisted cogeneration system with gas turbine and an absorption cycle based on $H_2O$-LiBr solution, in order to generate cooling using the heat from the SOFC exhaust. The authors analysed a 500 kW SOFC system which can supply 120 kW of cooling with a single stage VARS and 130 kW with a double stage VARS. In their analysis, the obtained exhaust gas temperature was around 280 $^{o}$C, which is quite low and thus the cooling capacity of the single stage and double stage VARS was relatively equal. Shariatzadeh et al [61] considered SOFC assisted hybrid tri-generation system fuelled by biogas produced from hospital waste. The study focussed on the thermodynamic and economic optimisation of 50 kW SOFC stack coupled to the absorption chiller via a heat recovery steam generator. The authors concluded that it is economically feasible to run such a system and it would result in a net profit of USD 874200 annually if the system is operated under optimum conditions. Chitsaz et al [62] simulated thermodynamic and greenhouse gas emission analysis of a novel tri-generation system assisted by SOFC and found that when SOFC is used as a prime mover to drive the system, the efficiency gain was 46% when compared to the SOFC being used as a standalone unit.

In a recent publication, Zhang et al [63] carried out numerical modelling for developing a hybrid system by integrating an MCFC with an absorption refrigerator as a bottoming cycle. They analysed the effect of the operating temperature of the fuel cell, the operating pressure of the fuel cell, the heat transfer coefficient of the working fluid used in the absorption refrigerator and the irreversibilities associated with both systems on the overall performance of the hybrid system. They found that the hybrid system performance improved with increase in operating temperature and pressure of the fuel cell and also with increase in heat transfer coefficient of the working fluid used inside the absorption refrigerator but decreased with increase in irreversibilities involved with the system. Besides mathematical modelling, no details of the heat exchangers used in the absorption refrigerator or the mode of coupling between the MCFC and absorption refrigerator were mentioned. The working fluid used in the absorption refrigerator was also not specified but looking at the block diagram used in their work it is envisaged that $H_2O$-LiBr must be the working fluid involved.

In comparison to the work presented by the authors above, Cachorro et al [64] suggested the concept of having a hybrid quad generation system which will deliver electrical power, heat, cooling and freezing capabilities, thereby taking the concept from CHP to CCHP (Combined Cooling  Heating & Power). They coupled an SOFC with an $NH_3$-$H_2O$ absorption chiller to meet the needs of a food processing industry and supermarket which are again stationary applications. Their system could deliver a total of 60 kW of cooling at a refrigeration temperature of 5 $^o$C and 30 kW of freezing at a refrigeration temperature of -20 $^o$C in addition to providing roughly 278 kW of both electrical and thermal power (for space heating). Although exact details of the different components used in the absorption chiller were not specified, certain recommendations on the kind of heat exchangers to be used for different components of the VARS were specified.

Chitsaz et al [65] carried out simulation of a CCHP unit which was coupled with a methane fed SOFC stack. The study considered and compared four different configurations – simple tri-generation system, anode gas recycle, anode and cathode gas recycle and cathode gas recycle from a thermodynamic and economic perspective. They concluded that the tri-generation system configuration with anode gas recycle has an energy efficiency of 82.5%, which was 6% higher than the normal tri-generation system. They also stated that amongst all configurations, the one that employed both anode and cathode recycle exhibited the highest thermodynamic and economic performance.

Table 5 summarizes the research work done on coupling of fuel cells with VARS and lists the main application of VARS in system integration.

Table 5: Summary of research on coupling of fuel cells and VARS

| Research group | Type of fuel cell used | Nature of work | VARS details/working pair | Main focus points of the paper | Application of VARS | Area considered for system implementation |
|---|---|---|---|---|---|---|
| Zink et al [43] | SOFC | Modelling | Double stage complete unit/ $H_2O$-LiBr | System integration studies, economic and environmental issues related to the system implementation | Space cooling/ heating | Buildings |
| Kazua Oshima et al [44] | PAFC | Simulation | Not specified | Types of heat recovery from the fuel cell for integration with VARS | Space cooling | Telecommunication equipment cooling |
| Zeting Yu et al [45] | SOFC | Modelling | Double stage Complete unit/ $H_2O$-LiBr | Study of effect of different SOFC operational parameters on the absorption chiller | Space cooling | Tri-generation for buildings |
| Darwish [47] | PAFC | Modelling | Single stage Complete unit/ $H_2O$-LiBr | Feasibility study of coupling fuel cell unit with VARS, idea of VARS supplementing the current VC system for buildings, distributed power generation for buildings | Space cooling | Buildings |
| Waragai et al [48] | PAFC | Working prototype | Single stage & double stage Complete unit/ $H_2O$-LiBr | System integration, heat recovery from PAFC, evaluation of cooling water temperature on VARS and the fuel cell | Space cooling | Telecommunication equipment cooling |
| Ishizawa et al [49] | PAFC | Working prototype | Double stage Complete unit/ $H_2O$-LiBr | Heat recovery from PAFC, operation of VARS for the whole year | Space cooling | Telecommunication equipment cooling |
| Sevencan et al [50] | MCFC | Economic analysis | Double stage Complete unit / $H_2O$-LiBr | Economic feasibility study for system implementation | Space cooling | Data centres |
| Yang et al [51] | PAFC | Modelling | Single stage Complete unit/ $H_2O$-LiBr | Operation of fuel cell with VARS in hybrid mode, effect of operational and functional fuel cell parameters on system performance | Not specified, but should be for space cooling | Stationary application |

| | | | | | | |
|---|---|---|---|---|---|---|
| Weber et al [52] | SOFC | Modelling and socio economic studies | Double stage Complete unit/ $H_2O$-LiBr | Decentralised system for buildings based on SOFC, calculation & comparison of emissions from conventional and SOFC based systems | Air conditioning | Buildings |
| Margalef & Samuelsen [53] | MCFC | Modelling | Double stage Complete unit/ $H_2O$-LiBr | Coupling of MCFC exhaust with absorption chiller, Thermal integration strategies between the two systems | Cooling and heating | Buildings |
| Arsalis [54] | HT- PEFC | Modelling | Single stage Complete unit with both $H_2O$-LiBr and $NH_3$-$H_2O$ | System integration, system matching, comparison to conventional systems | Cooling | Ship |
| Pilatowsky et al [55] | PEFC | Simulation | Single stage Complete unit/ monomethlyamine-water | Feasibility of using PEFC for cogeneration process, system integration | Air conditioning | Not specified |
| Frimodt & Mygind [56] | SOFC | Modelling | Double stage Complete unit/ $H_2O$-LiBr | Market study, system integration, system modelling, economic studies | Air conditioning | Buildings |
| Sarah Marie Martz [57] | MCFC | Modelling | Double stage Complete unit/ $H_2O$-LiBr | Steady state and dynamic modelling of VARS, system integration with MCFC, system operation and control | Air conditioning | Buildings |
| Mehrpooya et al [58] | SOFC | Modelling | Single stage Complete unit/ $NH_3$-$H_2O$ | Power plant design optimization, incorporation of VARS and rankine cycle for additional benefits | Not specified | Power plant |
| Zhao et al [59] | SOFC | Modelling | Single stage Complete unit/ $H_2O$-LiBr | Use of Coke Oven Gas to run SOFC, system integration of SOFC & VARS, optimal design parameter evaluation | Power plant cooling needs | Power plant |
| Takezawa et al [60] | SOFC | Modelling | Single and double stage complete unit/ $H_2O$-LiBr | Steady state modelling of VARS | Air conditioning | Not specified |

| | | | | | | |
|---|---|---|---|---|---|---|
| Shariatzadeh et al [61] | SOFC | Modelling | Not specified | Biogas fed SOFC assisted system-integration, system modelling and economic studies | Air conditioning | Building |
| Chitsaz et al [62] | SOFC | Simulation | Generator-absorber heat exchanger (GAX)/ $NH_3$-$H_2O$ | Methane fed SOFC system, steady state analysis, greenhouse gas emission | Air conditioning | Not specified |
| Zhang et al [63] | MCFC | Thermodynamic assessment | Single stage Complete unit/ $H_2O$-LiBr | Effect of different operating parameters on combined system performance | Not specified | Stationary application |
| Cachorro et al [64] | SOFC | Modelling | Single Stage complete unit/ $NH_3$-$H_2O$ | New concept of quad generation system providing power, heating, cooling and freezing capabilities | Refrigeration | Supermarkets & food processing industry |
| Chitsaz et al [65] | SOFC | Simulation | Generator-absorber heat exchanger (GAX)/ $NH_3$-$H_2O$ | Comparison between different configuration of tri-generation systems, economic assessment | Air conditioning | Not specified |

## 3.1 Discussion and analysis

The following general observations can be made from the summary of the research work presented above:

(i) Almost all the work related to coupling of fuel cells with VARS pertains to using the system for stationary applications either in buildings or for telecommunication equipment data centres. Only Arsalis [54] has talked about using it for mobile applications. This implies that most of the systems are designed for distributed generation having additional features of providing cooling and heat. This is totally understandable because high temperature fuel cells are mainly used for stationary applications.

(ii) The VARS in most of the cases is based on the $H_2O$-LiBr working pair and is designed as a double stage unit. As mentioned earlier, double stage VAR units have a higher COP than single stage VAR units but use more components, thereby increasing system complexity and weight. For stationary applications this is not much of a problem as the volume footprint is not an issue but this would be an issue on vehicles due to limited space.

(iii) The use of $NH_3$-$H_2O$ as the working fluid is not considered and this could be due to two reasons. The first being the impossibility of building a double stage VARS due to the need for extremely high system pressures and the second reason being the need for relatively high evaporator temperatures between 15 and 20 $^o$C for air conditioning purposes which can easily be met by the $H_2O$-LiBr working pair.

(iv) The preferred choice of fuel cell turns out to be either PAFC or SOFC. Between these two fuel cells SOFC is a high temperature fuel cell operating at temperature range 700-800 $^o$C while PAFC works between 150 and 200 $^o$C. As seen from Table 5, all VAR systems that are integrated with a PAFC are used for air conditioning purposes; hence the temperature at which thermal energy is supplied from the PAFC is sufficient to run an air conditioning system. On the other hand, in an SOFC the quality of residual heat available is excellent and thus provides sufficient thermal energy to drive the VARS for both air conditioning and refrigeration purposes. Also scaling down the quantity and quality of heat is easy when high

temperature fuel cells are involved. From the literature presented on coupling of fuel cells with VARS, the bar chart in Figure 8 shows the number of research groups who have employed different kinds of fuel cells for integration with VARS.

(v)    The method of heat recovery is crucial for system integration. Some of the research groups like Zink et al [43] and Pere Margalef [53] have employed direct exhaust gas coupling at the desorber. This method of thermal coupling might pose some challenges: first it might lead to corrosion at the cold end of the desorber and second the desorber might be too large in terms of volume, warranting more heat transfer area because the exhaust gas has a low thermal capacity. Other research groups have used a thermal coupling fluid, mainly water [44, 47, 54, 55] which is heated either by the fuel cell exhaust gas or by the fuel cell coolant loop.

(vi)   Design maps for operation of the fuel cell in terms of current density and other parameters are not delved into in the literature presented except for Zeting Yu [45] and Puquing Yang [51]. These two groups mention some details but the data presented is not sufficient. Hence there is need to relate the operating point of the fuel cell on the polarisation curve for optimal thermal energy generation in a CHP or CHCP application.

(vii)  When compared to the heat available from the engine exhaust which is intermittent in nature depending on the engine RPM, the heat available from the fuel cell is constant and thus the VARS operation can be relatively constant as well. This gives fuel cells an advantage over the internal combustion engine. Also, by varying the operating point of the fuel cell on the polarisation curve, the amount of heat generated can be either increased or decreased.

(viii) None of the systems discussed above have employed VARS for refrigeration purposes except for Cachorro et al [64] who have used it for a stationary application. Refrigeration sometimes requires sub-zero temperatures and space cooling in buildings does not. The cooling load is directly proportional to the evaporator temperature; hence sub-zero temperatures require a higher cooling load.
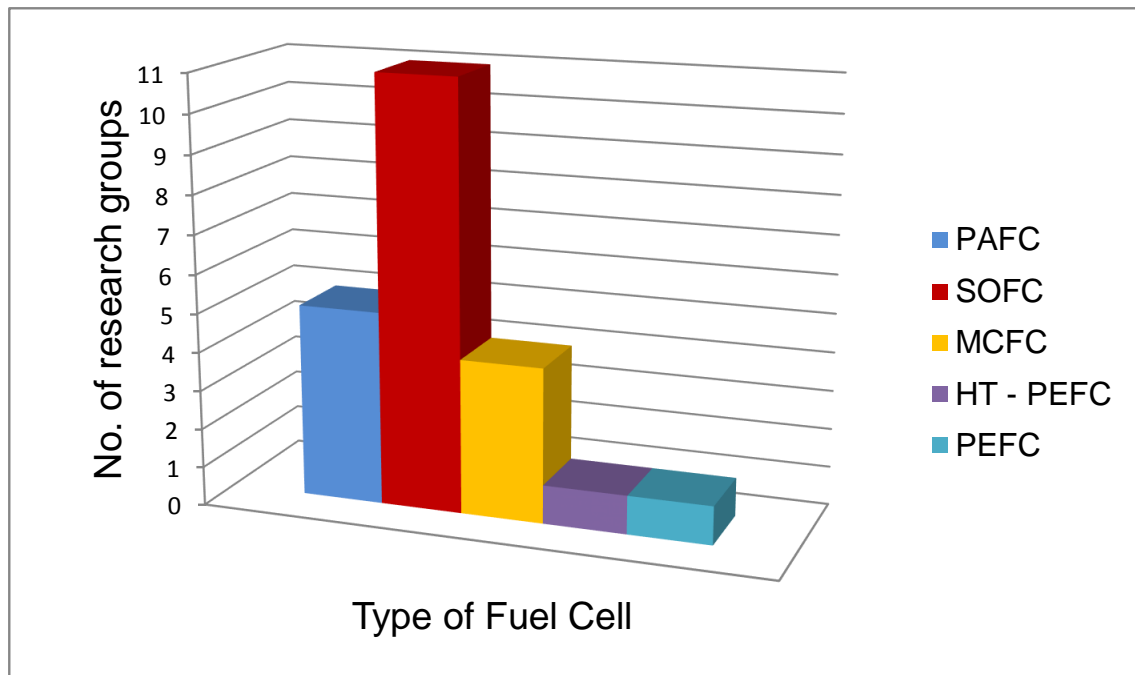
Figure 8: Fuel cell used by different research groups for integration with VARS

# 4 Fuel cells with VARS on vehicles

In the recent decade there has been an increasing interest on the adoption of fuel cells in automobiles in order to make them more environmental friendly and to either replace the conventional diesel engine or to reduce the load on the engine. Fuel cells on board the vehicle have been used both as part of the power train and as an APU (Auxiliary Power Unit). Increasing electrical demand especially on large trucks has necessitated the implementation of APUs in order to reduce the load on the main diesel engine. SOFCs fit into this category very well because they can run on reformed diesel and are more efficient than the diesel engine operating in idle mode. Some of the major players involved in developing SOFC APU's especially for heavy duty trucks include Delphi, AVL, Cummins Power Generation, and Eberspacher. Besides the activity carried out by major players other researchers have also looked into the prospect of using fuel cell auxiliary power units for trucks. The research activity and findings of both the major players and other researchers can be accessed through the following references [66-72]. A brief summary of some of the work mentioned in the above references is given below.

In the 'DESTA' project [66], the SOFC along with the BoP (Balance of Pant for fuel cell) was designed and developed as an APU (Auxiliary Power Unit) that could be packaged on a heavy duty truck. The electrical requirements for the truck were listed down initially and the APU was designed to meet all those requirements. The APU ran on reformed diesel and took over the role from the engine during idling. The fuel consumption decreased by 70% during vehicle idling due to implementation of SOFC APU when compared to the idling operation performed by the diesel engine itself. Not much information is given on the usage of residual heat form the SOFC and the sole purpose of the SOFC was to supply the electrical load on the vehicle.

Jain et al [68] carried out a techno-economic study for incorporation of fuel cell APUs on trucks. Their work concentrated only on the economic feasibility of employing a new technology - fuel cells as APUs on trucks. Their work and study is very important from an implementation point of view once all systems/components are in place but they do not chalk out any engineering aspects of such a system. There is no mention of integration of a VARS or any other thermally driven system with an SOFC APU on trucks or automobiles in general.

Rechberger et al [69] developed an SOFC APU demonstration system with methanol as the fuel. A table top model of the whole system was built in the lab and a control algorithm was developed which controlled the fuel supply, air supply and other critical parameters needed for stack operation. Once again the goal was integration of SOFC APU on the truck in order to reduce engine idling time and usage of sustainable fuels. The usage of exhaust heat from the SOFC was not mentioned and there was also no mention of integration of a thermally driven refrigeration system.

Other than a few patents [73-76] there is no published literature available on the use of heat from a fuel cell to drive the VARS on vehicles for either air conditioning or for refrigeration. Also, in these patents, only the concept and block diagram of a fuel cell heat driven refrigeration system is presented. No specifics on the system size, component design or other vital design information are presented. Hence it remains unclear if such a system exists only on paper as a concept or can it be practically realised.

One may argue that replacing the engine exhaust with the exhaust from a high temperature fuel cell will solve the issue but the lack of literature on this specific topic shows that nobody has studied in detail the integration of a fuel cell with a vapour absorption refrigeration unit on trucks or for that matter on any vehicle. Sizing of the fuel cell, effect of functional and operational parameters of the fuel cell on the VARS and on the fuel cell itself are some of the design criteria that need deeper analysis. If the fuel cell is employed on the vehicle, design consideration should be given towards the operating point of the fuel cell i.e. should the fuel cell be operated for maximum electrical efficiency or should a balance be achieved between the thermal and electrical energy generated within it. In addition, the fuel cell exhaust flow strongly depends on the fuel utilisation, which also affects the performance of the fuel cell; hence, some design maps would be vital in deciding the operating point of the fuel cell.

System integration of SOFCs with VARS on trucks and development of compact VARS could be an entirely new research area where more work is needed.

# 5 Outlook

As seen from the literature presented above, commercially available small scale VAR systems for mobile/automotive applications are very scarce. The idea of having a compact heat driven refrigeration system for trucks and other mobile applications is fascinating but in order to develop and implement it an altogether different approach needs to be taken. The problem is most research groups either try to use off-the-shelf available VARS units or try to scale down design of large components meant for stationary applications to the required size. Both of these approaches will not work because for a mobile application, a compact VARS with a volume footprint akin to the VC system is required and that requires bespoke design of compact high performance components.

Modelling and simulation followed by prototype construction is the way forward, but the modelling aspect needs to be extended a bit further other than mass and energy flows. The overall system model for any application provides critical insights however it must be supplemented by detailed component

level modelling and design. The modelling approach without design specification of the VARS components creates a void with respect to the technical feasibility of the concept. A grey area is created especially where small scale systems are involved and this warrants more research.

If absorption refrigeration systems have to be mounted and integrated on the vehicle then each part of it must be designed with proper geometrical and functional characteristics. This is because space is a major constraint on vehicles. Another important aspect is the presence of acceleration and vibration on automobiles/trucks and this might affect the performance of the VARS due to sloshing and other processes and these should be taken into due consideration when components such as the absorber and the desorber, in which fundamental processes take place, are designed. Also, if fuel cells are to be used on-board then appropriate operational maps for the fuel cell and effective heat recovery methods need to be designed

**Why using fuel cell heat driven refrigeration/ air conditioning systems could be a game changer in the auto industry?**

Development of thermally driven refrigeration systems along with SOFC units for trucks could potentially be a game changer for the truck refrigeration industry. The transition from conventional diesel engine powered VC units to the new system cannot happen overnight. The transition needs to happen in a phased manner. It is envisaged that in the initial phase (phase I), the SOFC will be incorporated as an APU  and it would take over the role of supplying power to the VC unit, other electrical loads on the vehicle and also assist in charging the battery if excess electrical energy is produced. This way the engine idling time will be drastically reduced and also overall efficiency of the vehicle will improve. In phase II, the VC unit can be replaced by a VARS unit and the SOFC will still perform the same functions assigned in phase I. In phase II, more electricity will be available from the SOFC because the refrigeration unit is being driven by heat and this will lead to hybrid power train design configurations on the vehicle. In the final phase (phase III), the diesel engine can be completely be eliminated and the powertrain design will be a combination of PEFCs (Polymer Electrolyte Fuel Cells) and SOFCs and the refrigeration system on-board will be a thermally driven one. In this futuristic scenario, the vehicle will be completely emission free, very quiet and the refrigeration unit will be running on residual thermal energy which would otherwise be dissipated.

Such a system will definitely increase vehicle efficiency, reduce emission and noise from these vehicles.

Finally, development of small scale VARS units that could run effectively using heat from the SOFC exhaust or any high temperature fuel cell exhaust could potentially find use in a wide variety of applications. Replacement of VC units with VARS units running off residual thermal energy available from the vehicle will aid in the use of refrigerants that have lower Global Warming Potential (GWP) and also pave the way for using valuable electrical energy needed for the compressor today for other purposes.

# 6 Conclusions

After a thorough review of the applicability of VARS technology for the transport sector (or on a small scale), the following conclusions can be drawn:

i. Although the technology itself is quite mature, there are still engineering challenges that need to be overcome if this is to be implemented in areas where the VC technology is currently dominant.
ii. In order to compete with VC technology, the VARS should occupy the same volume footprint and should be capable of delivering a similar performance.
iii. The preferred working fluids are still $H_2O$-LiBr or $NH_3$-$H_2O$ and each working fluid has its own advantages and disadvantages. Perhaps this could be the limiting factor when scaling down VARS units under 10 kW. New working pairs should be explored and their implications on component sizing should be investigated.
iv. COP and cooling capacity although interlinked are two different terms and must not be confused with one another. As seen from the literature presented, it is very much possible to have a high cooling capacity but the COP can be quite low.
v. The cooling demand- from both air conditioning and refrigeration is going to increase manifold and the energy required to meet that is going to increase proportionally. If residual energy (which would otherwise be dissipated or wasted) can be used in ways to run these systems, a significant portion of energy can be diverted to high priority applications or places which critically need them.
vi. Microchannel and mini-channel heat exchanger technology and research on fundamental heat transfer on these devices will certainly help in development of VARS technology for small scale applications.

And at last

vii. Fuel cell technology will definitely penetrate the automotive industry and the stationary distributed power generation sector. Harnessing the heat from the fuel cell, for use in another application, will not only boost the system efficiency but also contribute to maximum internal use or recycling of energy within the system rather than wasteful dissipation.

## Acknowledgements

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