Heat Pipe heat exchangers for air conditioning applications

Vikrant Venkataraman,
VenkaCon – Research & Technical Consulting (www.venkacon.com), Graz, Austria,
vikrant.venkataraman@outlook.com

Abstract

Next generation air conditioning and cooling technologies must be environmentally friendly and sustainable. Using residual and renewable heat, wherever possible, to generate cooling will go a long way in reducing energy demands from cooling needs. This is particularly important in hot and tropical climates where for most part of the year, temperatures are almost always above 30 °C, resulting in enormous amounts of energy needed for cooling. In this report, we investigate how residual/waste heat from Solid Oxide Fuel Cells and other heat sources can be integrated into an absorption refrigeration system to generate cooling. An outline of the broad system, followed by detailed methodology for component and system development and fundamental thermodynamics will help the reader grasp the concepts better.

Keywords: Solid Oxide Fuel Cells, Heat Pipes, Advanced Heat Transfer, Sustainable Cooling, Thermal Energy

1. Introduction

Humans need a comfortable temperature indoors when the outside ambient temperature is in the extremes – either very cold or very hot. This is where climate conditioning and control systems come into play, providing the perfect temperature so that people can enjoy themselves and live comfortably. Extreme cold and hot ambient temperatures exacerbate the need for deploying heating ventilation and air conditioning (HVAC) systems and units for climate control since uncomfortable temperatures can lead to a range of illnesses and problems [1].

People living in hot and tropical climates, such as South East Asia, the Middle East and Africa experience temperatures above 30 °C for most part of the year and up to 50 °C in the hottest summer months which can last anywhere between one and two months. Out of the roughly 2.8 billion people living in the hottest parts of the earth, the regions mentioned above, only 8% have access to air-conditioners (AC) as compared to 90% ownership in the United States of America and Japan which are not typically considered to be hot and tropical [1]. Now this puts almost 35% of the world's population in a situation where people have to struggle to attain thermal comfort due to the simple reason of not being able to afford the unit and its corresponding operating costs. The energy needed for cooling and air conditioning is enormous [1] and is bound to only increase in the coming decades [1] due to rise in population numbers, rise in living standards of people and migration of people from rural to urban areas. It is estimated that the energy needs from space cooling will triple by 2050 [1] and that means a lot of energy going into space cooling. Air-conditioners and electric fans used for cooling rooms and spaces account for 20% of the total electricity demand of buildings around the world [1], some studies claim this number to be between 40 and 60% of the total electricity demand of buildings [2]. This constitutes a major chunk of the energy needs and cutting down this percentage will free up electrical energy (electricity) to be used for other purposes in other applications, for e.g. charging of Electric Vehicles (EVs) or for electrolysis for hydrogen production. Electrical energy is a high-quality form of energy or in thermodynamic terms, high in exergy whereas thermal energy is a low-quality form of energy or low in exergy. Wherever possible, if a low-quality form of energy can perform the same task as a high-quality form of energy, one can expect considerable savings in energy.

While district heating systems, to supply hot water for room heating, are widely prevalent and deployed in the western part of the world, the same cannot be said for district cooling systems although the projects and plants for district cooling systems is on the rise and becoming a standard especially in rich developed countries (such as Singapore, Saudi Arabia) that fall under the category of 'Hot, humid, or tropical'. These district cooling systems supply chilled water at approximately 10 ^{o}C via piped networks to buildings which can then be circulated to closed spaces for space cooling. Some studies [3] question the effectiveness of chilled water circulation via radiators (akin to those used for hot water circulation) for effective space cooling. The reason for this is simple. When hot water, at 50 or 60 ^{o}C is being circulated through the radiators, to heat the room during winter, the temperature gradient for heat transfer is at least 40 or higher (depending on the ambient temperature of the room). When chilled water at 10 ^{o}C is circulated through the radiator, to cool the room during summer, the temperature gradient for heat transfer is 30 or below (depending on the ambient temperature of the room) and this results in ineffective heat transfer and thus ineffective cooling of the room as required for thermal comfort. To achieve a higher temperature gradient with chilled water, it must be cooled even further, and this will consume an additional amount of energy and is more cumbersome than installing an electric air-conditioner or an electric fan. Detailed energy studies must however be carried out to have a comparison between the costs of operating a district cooling system in comparison to individual air-conditioning units.

The number of electrically driven air-conditioners deployed globally is roughly around 2 billion [4] and with the growing demand for cooling, it is envisaged that two-thirds of households around the world will possess an air-conditioner by 2050. This in turn leads to higher need for electrical energy per household and if this electrical energy does not come from renewable sources, it leads to higher CO_2 emissions and this vicious cycle continues as the demand for space cooling grows. Cooling contributes roughly between 3.4 and 4 % of global emissions [5] and reducing this percentage is one step towards climate protection.

Electrically driven air conditioning units (both large and small) used today are based on vapour compression (VC) technology and these are the kind of units that people usually buy when they seek to get a respite from the heat. This works great when the number of units installed is a few and the electricity grid is strong. However, this is not the most sustainable solution for reasons just explained above. The most efficient air conditioners cost a lot to purchase but provide savings in the long run [4] but customers tend to opt for the cheaper ones which are low on energy efficiency and this inefficiency puts considerable strain on the electricity grid and can account for over half of the peak electricity demand during the hottest days. Just like how the world is transitioning to generating more renewable electricity via solar and wind, it is also vital to generate heat using solar energy and also use residual heat, from systems such as Solid Oxide Fuel Cells and others, to the maximum extent possible in order to bring down the electrical energy needs from cooling. This is where technology development in thermally driven cooling and refrigeration systems will play a crucial role.

The higher the ambient temperature the higher is the need for space cooling and the corresponding energy demand. The need for thermally driven cooling systems also arises from the fact that the cost of building, maintaining and operating electricity networks and systems to cater to peak demand is two to four times the cost of that needed for base load electricity generation [1]. It is envisaged that thermally driven cooling systems will help in reducing both the peak and base load demand in electricity and thereby primary energy consumption and in turn greenhouse gas (GHG) emissions provided they are engineered and designed to meet the end user requirements.

This chapter will look into how Solid Oxide Fuel Cells and other heat sources can be integrated into an absorption refrigeration/cooling system to generate cooling. Utilising residual and renewable heat will help in making cooling more sustainable and less energy intensive. Some of the key aspects that will be looked into in this report are as follows:

- What sources of heat can be tapped into? And how can heat be transported?
- What role can heat pipes play in modern heat exchangers and heat transport networks?
- How can heat driven cooling systems reduce energy demand and in turn CO_2 emissions?

2. Technologies for sustainable cooling – Solid Oxide Fuel Cells, Absorption Refrigeration, Solar Thermal, Heat Pipes

In this section, we will take a look at the technologies that will help in progressing to sustainable space cooling. The technologies that can make this happen are: *Solid Oxide Fuel Cells*, *Absorption Refrigeration System*, *Solar Thermal Energy Systems* and *Heat Pipes*. By integrating these technologies in a holistic way, the electricity demand for cooling can be drastically reduced. The key to do so is to harness renewable heat sources (Solar Thermal), integrate secondary heat sources (Solid Oxide Fuel Cells) and develop an individual unit or a system (driven by thermal energy) that is able to cool down the space and achieve the temperature needed for thermal comfort.

2.1 What is a Solid Oxide Fuel Cell?

A Solid Oxide Fuel Cell (SOFC) is a high temperature electrochemical device that converts chemical energy of fuel to electricity and high-quality heat. The temperature of operation of current state of the art SOFC cells is between 600 and 800 ^{o}C [6, 7, 8] and research is underway to further bring down the operating temperature. An SOFC is a multi-fuel compatible device meaning a wide range of fuels can be used in them for power generation and this aspect is critical for future power generation systems. However, among the different fuels only hydrogen, methane and biogas (after cleaning) can be directly fed into the SOFC stack. The rest of the fuels warrant a fuel reformer or a cracker prior to the stack so that the fuel is reformed or conditioned to an extent that is compatible with the stack.

The basic schematic of a single Solid Oxide Fuel Cell is shown in Figure 1.

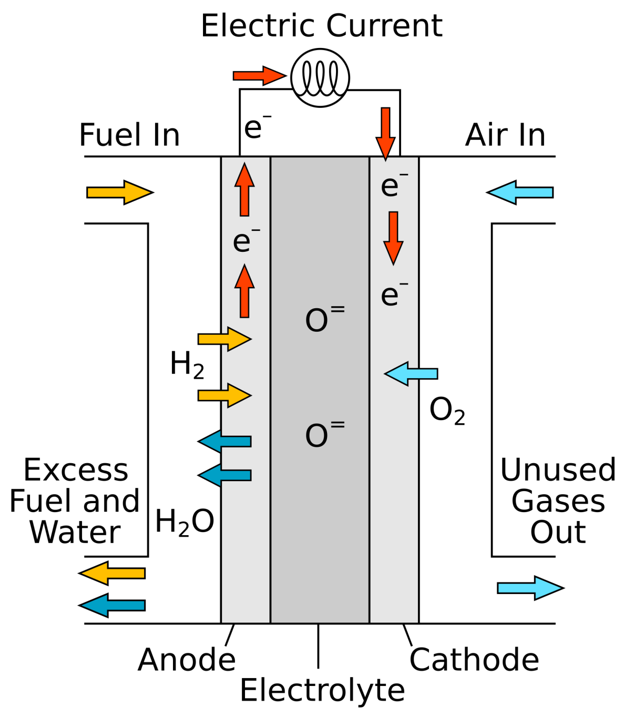

Figure 1: Schematic of Solid Oxide Fuel Cell [9]

When many cells are put together, a stack is formed and stacks can then be assembled together along with other auxiliary components (such as heat exchangers, pumps, sensors, blowers etc.) to form a system. SOFC systems for power generation based on biogas or biomethane as fuel is envisaged to be a game changer in the power generation business due to the high efficiencies achievable and low emissions generated. SOFCs powered by biogas will complement solar, wind and other renewable sources of electricity generation. Biogas is 100% renewable and can be generated with current technologies at prices that are acceptable for the market [10]. The electrical efficiency of such a system is close to 55% and the combined heat & power (CHP) efficiency is close to 90% [11].

The reader is encouraged to refer to standard textbooks on high temperature fuel cells [12] for detailed and in-depth information on different technical aspects of SOFCs.

2.2 Absorption Refrigeration System

Absorption Refrigeration System, also known as Vapour Absorption Refrigeration System (VARS) is a thermally driven system which requires heat rather than electricity as input to drive the compressor. The compressor in a VARS is the desorber and the absorber together. A schematic of the VARS is shown in Figure 2.

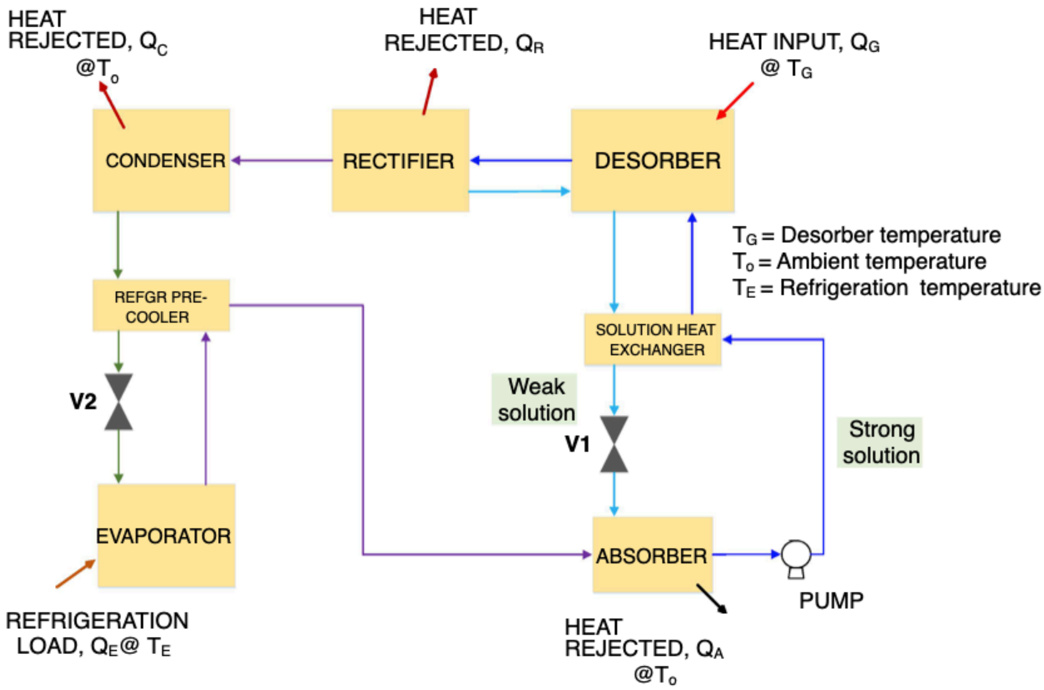

Figure 2: Schematic of Vapour Absorption Refrigeration System

The desorber, rectifier, condenser, refrigerant pre-cooler (Refgr pre-cooler in Figure 2) and solution heat exchanger form the high-pressure part of the VARS and the evaporator, absorber and solution pump form the low-pressure part of the VARS. Key advantage of the VARS is that the amount of electricity needed to run the system is significantly lower when compared to VC systems. The reason for this is because in a VARS, it is the liquid that is pumped to a higher pressure whereas in a VC system it is gas which needs to be compressed to a higher pressure. Compressing a gas is more energy intensive than compressing a liquid and that is the fundamental difference in the energy consumption levels between the two cooling systems.

The temperature needed at the desorber of the VARS is between 100 and 200 ^{o}C, depending on the amount of cooling and evaporator temperature needed [13]. A temperature of 100 ^{o}C at the desorber end along with sufficient thermal energy is deemed to be sufficient for maintaining a temperature between 18 and 24 ^{o}C at the evaporator (needed for thermal comfort) and this is easily achievable from renewable or residual heat. More detailed information on absorption systems can be found in [14].

2.3 Heat Pipes – what are they?

Heat pipes are isothermal devices that simply transfer heat from one end to another. They are able to transport large quantities of heat by making use of the latent heat capacity (change from liquid phase to vapour phase and back to liquid phase) of the working fluid present inside it. The basic schematic of a heat pipe is shown in Figure 3.

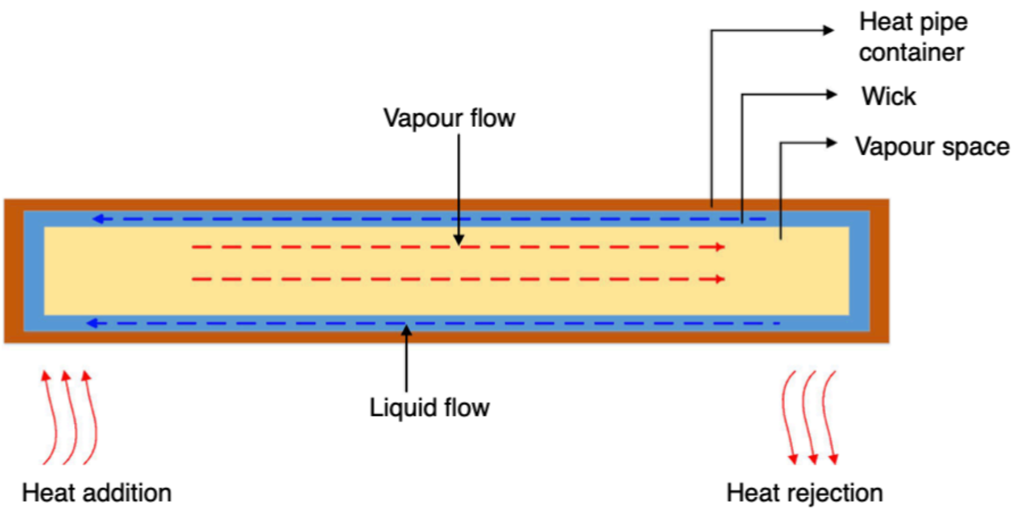

Figure 3: 2D Schematic of Heat Pipe

A heat pipe has three sections namely *evaporator*, *adiabatic,* and *condenser*. The outer shell of the heat pipe is made of metal and there is a porous wick structure inside the metal (this is one type of heat pipe) which helps in the transport of the working fluid from one end to the other of the heat pipe. Some heat pipes also function without the wick structure. The evaporator section is the place where heat is added to the heat pipe which then gets transported all the way to the condenser section where heat is expelled.

The key advantages that heat pipes [15] have are:

- Very high thermal conduction
- Fast response to thermal loading
- Quiet operation
- Reliability
- Absence of moving parts
- Well defined temperature of delivery

The above advantages make them an ideal candidate to transport heat in the most efficient manner from the place of generation (source) to the place of use (sink). Heat pipes come in different shapes with different materials and working fluids for different applications and that makes them highly versatile for use. The reader is referred to standard textbooks on heat pipes [15, 16] to gain in-depth knowledge on these devices.

Some of the common working fluids used in heat pipes and their useful temperature range is given in Table 1. The choice of the working fluid will determine the thermal performance of the heat pipe and the temperature range in which it can be operated for use in an application.

Working fluid	Useful temperature range (°C)	Boiling point at atmospheric pressure (°C)
Water	30 – 200	100
Toluene	50 – 200	110
Flutec PP9	0 – 225	160
Heptane	0 – 150	98
Thermex	150 – 350	257
Flutec PP2	10 – 160	76

Table 1: Commonly used working fluids in heat pipes

2.4 Solar Thermal Energy System

A solar thermal energy system is able to capture sunlight (solar energy) and convert it to thermal energy by means of a collector. They are usually classified into low, medium and high temperature collectors depending on the temperature required for the end application that they are catering to. Temperatures anywhere between 30 and 1000 °C [17] are achievable with solar thermal technology. Among solar thermal collectors, there are two types- *non-concentrating* type and *concentrating* type. In the non-concentrating type, the area that intercepts the solar radiation is the same as the area that absorbs the solar energy. In the concentrating type, the area that intercepts the solar radiation is several times greater than the absorber area. The former is easy to install, does not require a special tracking system and is cost effective but the downside is achievable temperatures are limited to 200 °C. This is the type that is installed at most residential homes and buildings. Even though the maximum temperature is limited to 200 °C, it is not an issue as far as its integration with VARS is concerned as the maximum temperature needed at the desorber is 200 °C.

The basic principle of operation of a non-concentrating type of solar collector is as follows [18, 19]: A tube collector is installed on the roof of a building, on the surface that is exposed to sunlight. The tubes in the tube collector hold a heat transfer fluid, for e.g. water or propylene glycol-water mixture which gets heated by the solar insolation. The heat transfer fluid then evaporates and transfers its heat to a thermal energy storage unit (which usually contains water) and flows back to the tube collectors for the process to start all over again. One such design is shown in Figure 4.

There are textbooks and tools [21, 22] that are widely available which help in the design of such solar thermal collectors. The reader is highly encouraged to refer to these sources for deeper insights and knowledge.

Now that we have some understanding and insights into these four technologies, let us take a look at how they can be integrated together to enable cooling solutions that are sustainable and less energy intensive.

Figure 4: Schematic of Solar Energy Thermal System (Non-Concentrating Type) [20]

3. Ways and means to tap residual & renewable heat

Just as how innovation has progressed in the field of solar cells, for generating electricity, and has reached widespread market penetration, the same must be achieved for tapping solar thermal energy and residual thermal energy wherever and whenever possible. This heat can then be immediately used for space cooling or stored for later use for other purposes. Tapping solar thermal energy for hot water generation is quite well known. However, tapping thermal energy and using it to drive a cooling system in a continuous manner is still a challenge but if done correctly will make space cooling sustainable and environment friendly.

As mentioned earlier in section 2, a temperature between 100 ^{o}C and 200 ^{o}C is needed at the desorber end of the VARS and this can easily be achieved by tapping heat either from SOFCs or from solar. In this process, heat pipes will play a key role in tapping and transporting this heat in the most effective and efficient manner.

3.1 Tapping heat from Solid Oxide Fuel Cells

As mentioned in section 2.1, SOFCs are high temperature devices, and this means there is immense scope for tapping residual heat from these units and systems. The heat from an SOFC system can either be directly taken from the stack or from the exhaust of the SOFC system. If one does not make use of the residual heat from an SOFC then it is dissipated to the environment and that means high-quality exergy (which can be put to work) is permanently lost to the environment.

There are couple of ways for transferring heat from a Solid Oxide Fuel Cell system to the desorber of the VARS [23]. Some of the ways are mentioned below.

3.1.1 Direct plugging at both ends

With direct plugging, the heat pipe is embedded on both ends *viz.* The SOFC stack and the desorber of the VARS as shown in Figure 5.

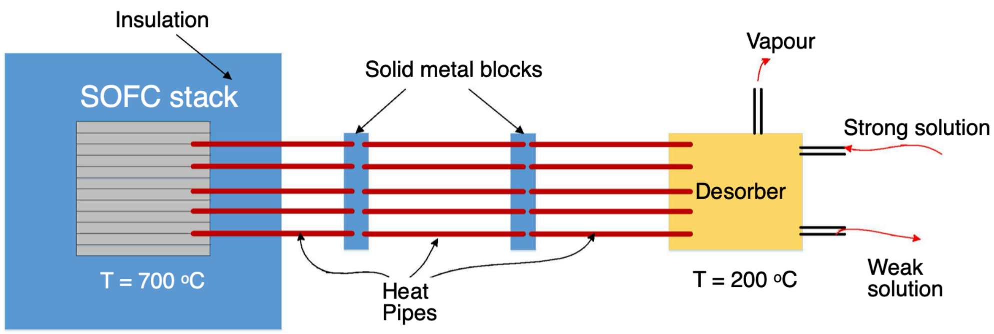

Figure 5: Direct Plugging of heat pipes at both SOFC and Desorber end [23]

The temperature at the SOFC stack side is between 600 and 800 ^{o}C and that at the desorber side is around 200 ^{o}C maximum. Hence, there needs to be some metal blocks placed between the SOFC and desorber in order to achieve temperature compatibility at both ends. This is because the heat pipe is an isothermal device. Design of the individual heat pipes between the metal blocks needs to be done carefully in order to achieve the desired heat transfer. Through this design not only is thermal energy (or residual energy) transferred to the desorber but also the SOFC stack temperature is maintained at the desired operating value which is critical for stack operation.

3.1.2 Direct plugging at one end

In this design, the heat pipe is embedded only at the desorber end and the other end is either

- Placed adjacent to the SOFC stack within the insulation – Option 1

(or)

- Exposed to hot cathode exhaust – Option 2

Both options offer flexibility as far as heat transfer to the heat pipe(s) is concerned. In the former, the heat pipe can be moved around anywhere in the space between the stack and insulation, to vary the heat flux that gets into the heat pipe while in the latter, the cathode exhaust flow rate and temperature can be varied which in turn varies the heat flux and in turn transfer rate. Figure 6 and Figure 7 show one visualisation of how this concept can be realised.

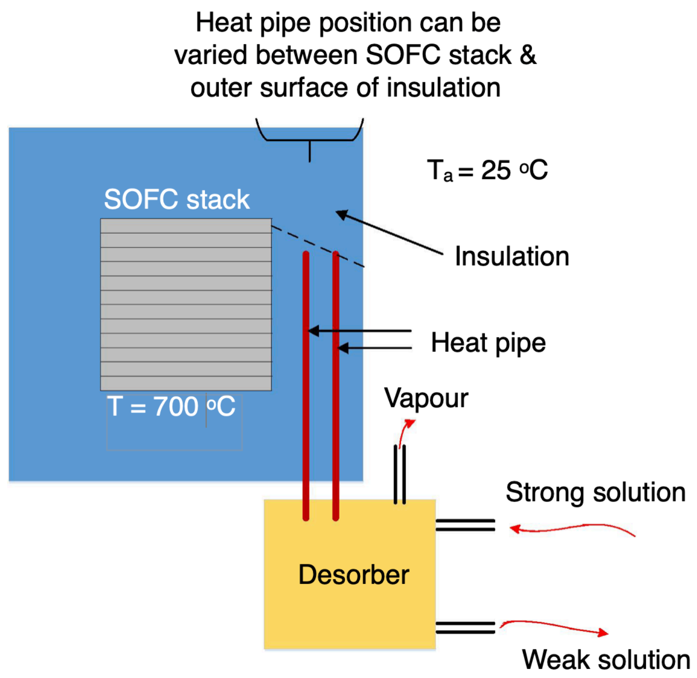

Figure 6: Direct Plugging only at Desorber end, Option 1 [23]

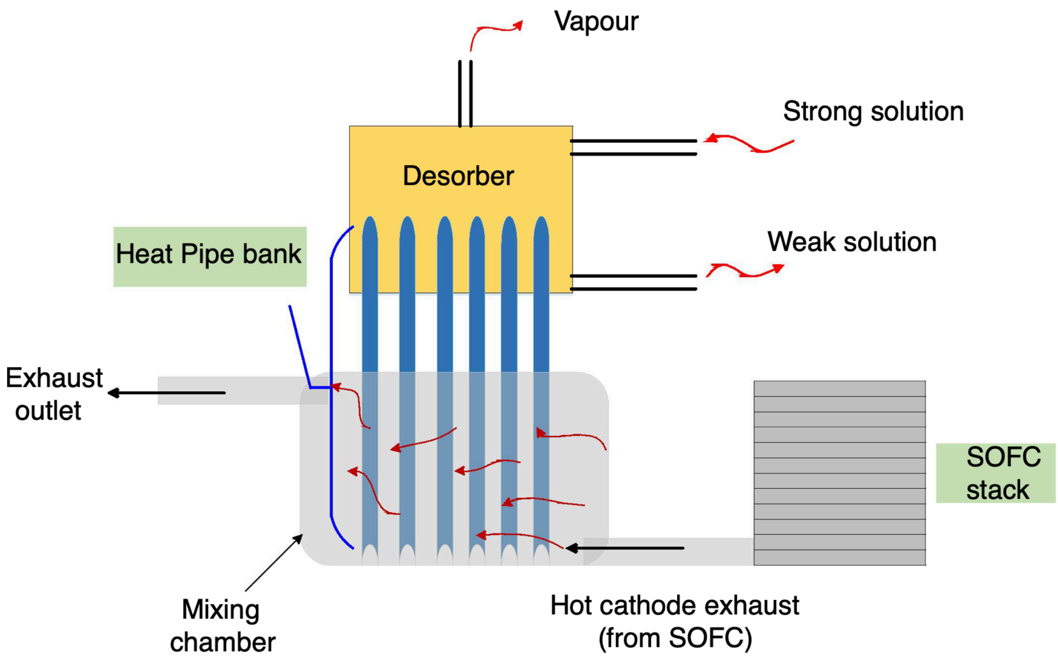

Figure 7: Direct Plugging only at Desorber end, Option 2 [23]

3.1.3 Use as a heat exchanger

In this configuration, there is no plugging of the heat pipes either at the desorber or at the SOFC end instead it is used as a heat exchanger in which thermal oil is heated by the hot cathode exhaust to the required temperature. The hot thermal oil is then used as a coupling fluid in the desorber. The thermal oil can also be replaced with any other heat transfer fluid that is compatible with the operating temperature range needed at the desorber. Figure 8 shows this concept.

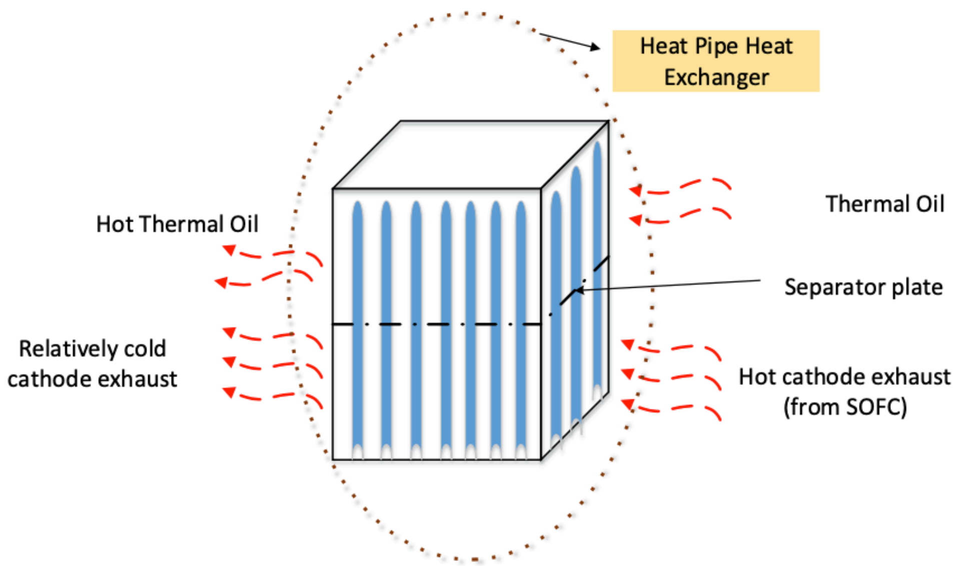

Figure 8: Use of Heat Pipes in a Heat Exchanger Configuration [23]

3.2 Tapping heat from Solar

Heat (or thermal energy) can easily be tapped from solar radiation using solar thermal collectors mentioned in section 2.4. These devices convert solar radiation into heat which gets absorbed into a heat transfer fluid (HTF) and is then transported to the specific application where thermal energy is needed. It is envisaged that both the temperature and quantity of heat that can be achieved from solar radiation is sufficient to drive the desorber of the VARS.

The ways in which the heat can be transferred to the desorber of the VARS is as follows:

3.2.1 Direct transfer via HTF

In this method of heat transfer, the HTF directly transfers heat to the desorber of the VARS. The heat transfer will be in a closed loop cycle from the solar thermal collector to the desorber of the VARS and back as depicted in Figure 9. There is one heat transfer loop involved and the control panel ensures the flow rate and temperature of the HTF at the desorber inlet is in line with the cooling output desired from the VARS.

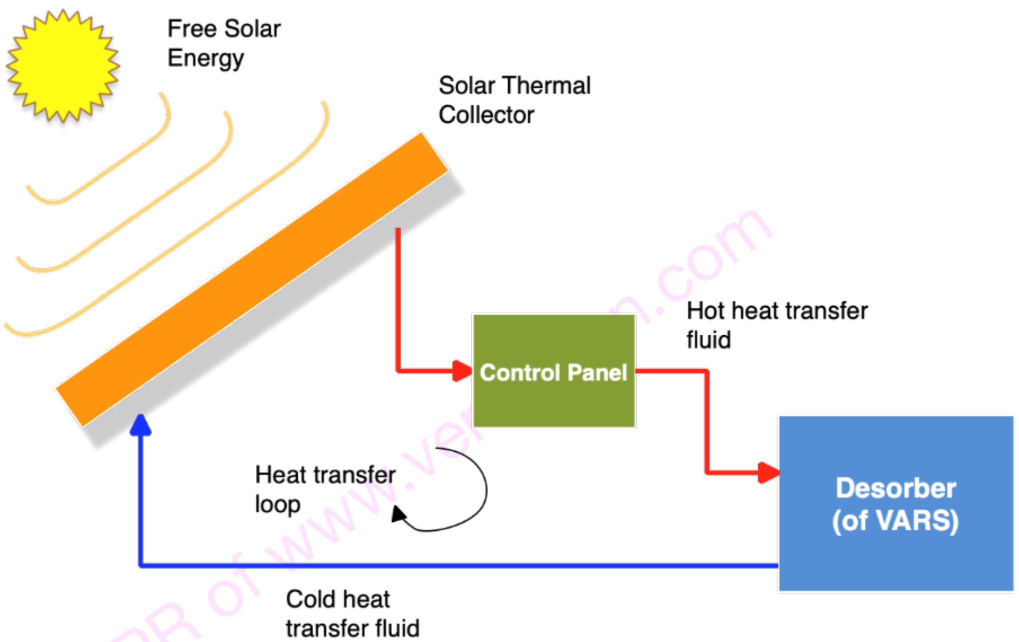

Figure 9: Direct Transfer to desorber via Heat Transfer Fluid

3.2.2 Indirect transfer via Heat Pipes

In this method of heat transfer, the HTF transfers heat at the evaportaor section of the heat pipe heat exchanger. This heat is then transported along the length of the heat pipe and given out at the condenser section which is directly embedded at the desorber of the VARS. This method is to be employed where the HTF cannot be directly coupled to the desorber of the VARS. The heat transfer comprises of two loops – first from the HTF to the heat pipe and second from the heat pipe to the desorber. The schematic of this concept is shown in Figure 10.

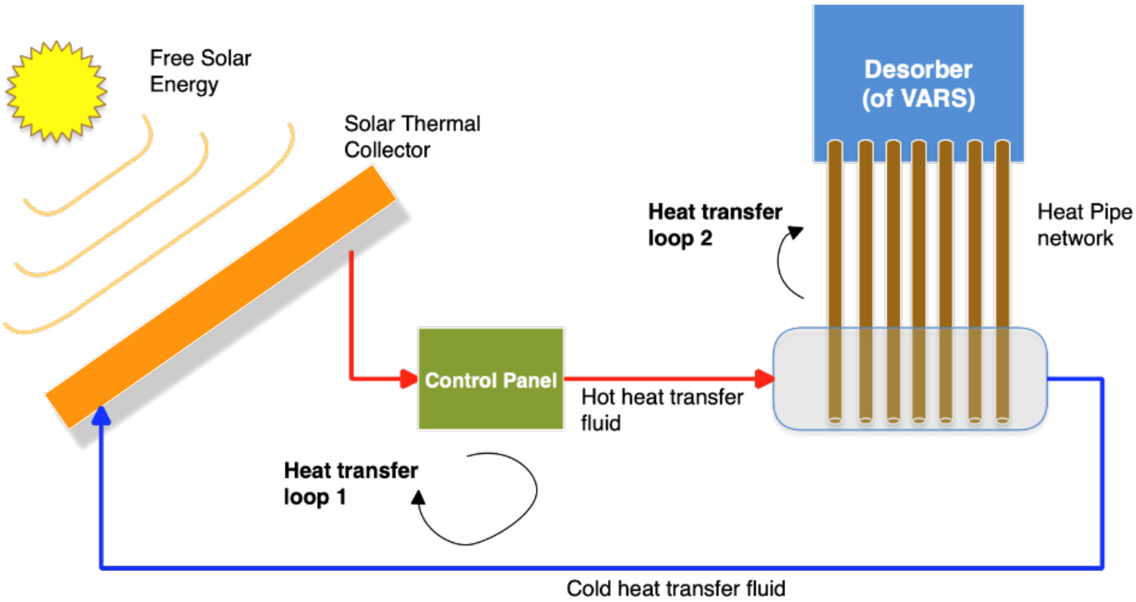

Figure 10: Indirect heat transfer to desorber via heat pipes

The role of the control panel once again is in regulating the flow and temperature of the HTF.

3.2.3 Direct plugging at both ends

In this concept, the heat pipes are directly embedded on the solar thermal collector at one end and on the desorber at the other end. This facilitates direct transfer of heat from the solar thermal collector to the desorber of the VARS. The schematic representation of this concept is shown in Figure 11. Heat pipes in this configuration need to be twisted and bent in order to route them appropriately.

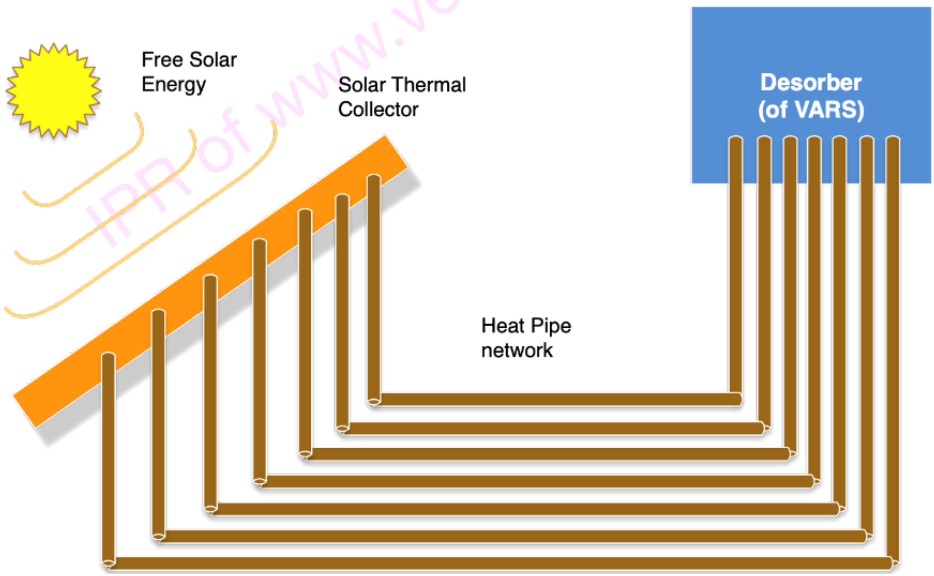

Figure 11: Direct Plugging at both ends

3.3 Why heat pipes are better than conventional heat exchangers?

The heat (or thermal energy) available from SOFCs is classified as residual heat and that from solar is classified as renewable heat. The reason why they have been termed so is because the thermal energy that can be tapped from an SOFC is the by-product of the electrochemical combustion process and the thermal energy that can be tapped from solar is abundantly and freely available. Once the heat can be tapped effectively from the respective sources, this needs to be transported to the end location where it will be used. It will be most ideal if the temperature at which heat is tapped from the source is the same as the temperature at which heat is delivered to the sink because this gives the possibility to bring down the temperature if needed and also to tweak the heat flux levels. This is where heat pipes come into play as they are extremely efficient in transporting heat and there is very little temperature drop along the heat pipe. One can say that they act like a thermal bridge. If the same process were to be done via conventional heat exchangers, then there will be a lag in the thermal response and also the temperature and quantity of heat delivered can be lower than that of what is possible via a heat pipe and will warrant a whole range of coupling fluid circuitry (pumps, valves regulators etc.)

Heat pipes being isothermal devices, have the capability of transporting large quantities of heat with a very high thermal response and all these can be done by tweaking the designs of the heat pipe. They can also be twisted and bent into several shapes and that makes it convenient to move heat from the place it is produced to the place where it is needed (in this case mainly VARS)

Heat pipes can be used in the following areas of a VARS:

- Desorber
- Absorber
- Evaporator &
- Condenser

At the desorber, heat pipes aid in boiling of the refrigerant-absorbent solution, generating refrigerant which then circulates through the rest of the components of the cooling system. At the condenser, heat pipes can transport the heat out of the condenser, and at the evaporator heat pipes can aid in getting heat into the evaporator. Finally, at the absorber where the process is exothermic, heat pipes can once again aid in removing heat from the component to the ambient.

The key advantage that heat pipes have over conventional heat exchangers [2] (e.g. plate heat exchangers, shell & tube, tube & fin etc.) is summarised in the points below

i. The thermal response, which is the speed at which a device responds to sudden changes in temperature, of the heat pipe is orders of magnitude higher than conventional heat exchangers.
ii. High compactness and extremely flexible in arrangements.
iii. Complete separation of hot and cold fluids.
iv. Unidirectional heat transfer. This means the heat pipe acts like a thermal diode.
v. Modularisation- Each heat pipe can be considered as a separate entity, and this adds resilience to the heat pipe heat exchanger preventing single point of failure.
vi. Heat pipes can be less bulky than conventional heat exchangers.
vii. Ease of maintenance.
viii. Relatively less equipment in fluid circuitry.

4. System design and integration

Now that we have looked into the technologies that are needed and will enable generate cooling from thermal energy, it will be of interest to the readers to gain further insights on how this can be accomplished for apartment buildings, individual homes and other community living houses, especially for countries that fall under the ‘hot and tropical’ category. This section provides some designs on how heat driven cooling systems can be implemented, configured and designed for different scenarios and use cases.

The key in reducing dependence on electricity (or electrical energy) for space cooling, especially in hot and tropical climates is to develop a small and medium scale VAR system (or other heat driven cooling systems) that ideally has a similar volume footprint when compared to a VC system and can generate sufficient cooling for thermal comfort. These systems must be able to cool the space and maintain a temperature between 18 and 24 ^{o}C which is the requirement in most cases.

4.1 Solar heat driven VARS – One apartment building

Solar heat also defined as renewable heat, as mentioned earlier in this chapter, is freely available for over 200 days in a year (or 12 hours x 200 = 2400 hours) [24] in hot and tropical countries and this can be made use of in operating a thermally driven cooling system. One way to practically implement them in an apartment building is given in Figure 12.

As seen from Figure 12, the building has four individual apartments and each of these need an air-conditioning unit. The VARS unit, with all its components, is to be packaged in such a way that the evaporator is inside the space (of the building) which needs cooling and the rest of the components *viz.* desorber, absorber and the condenser are placed outside the space. This is because the condenser and absorber release heat and the desorber needs to be supplied with external heat. The thermal energy for driving the VARS comes from the solar collectors installed on the roof of the building and the means to transfer heat to the desorber is from one of three ways mentioned in section 3.2. If heat transfer fluid is used to supply heat at the desorber, then they have to be channeled via pipes and brought down to the individual units installed at various apartments. In case heat transfer to the desorber is via heat pipes then these have to be routed appropriately along the building structure and also brought down to the individual units.

The same concept can be extended to buildings with more than four apartments.

4.2 VARS coupled with Solid Oxide Fuel Cells – One apartment building

Many of the apartment buildings in developing countries have a diesel-based generator on their premises in order to supply electrical power during outages. This diesel-based generator comes into action only when there is an interruption in the grid electricity supply and thus does not run continuously. Replacing this diesel-based generator with an SOFC system running continuously on biogas will not only complement renewable electricity supply, by adding resilience to the network, but also will lead to an environmentally friendlier way of generating electricity with high efficiency. The efficiency of diesel-based generators is around 25% [25] and depends on the operating conditions. The SOFC system is not only going to generate electricity but also sufficient heat which can be tapped into. The individual VAR units are placed at each of the apartments, in the manner as described in section 4.1, and the heat to each of these VAR units is supplied via one of three ways described in section 3.1. The same concept can of course be extended to buildings with more apartments, the only pre-requisite being the existence of an SOFC system at the premises of each apartment building.

Note: The SOFC system can also be replaced with another system that generates sufficient residual heat. Figure 13 shows the visualisation of this concept.

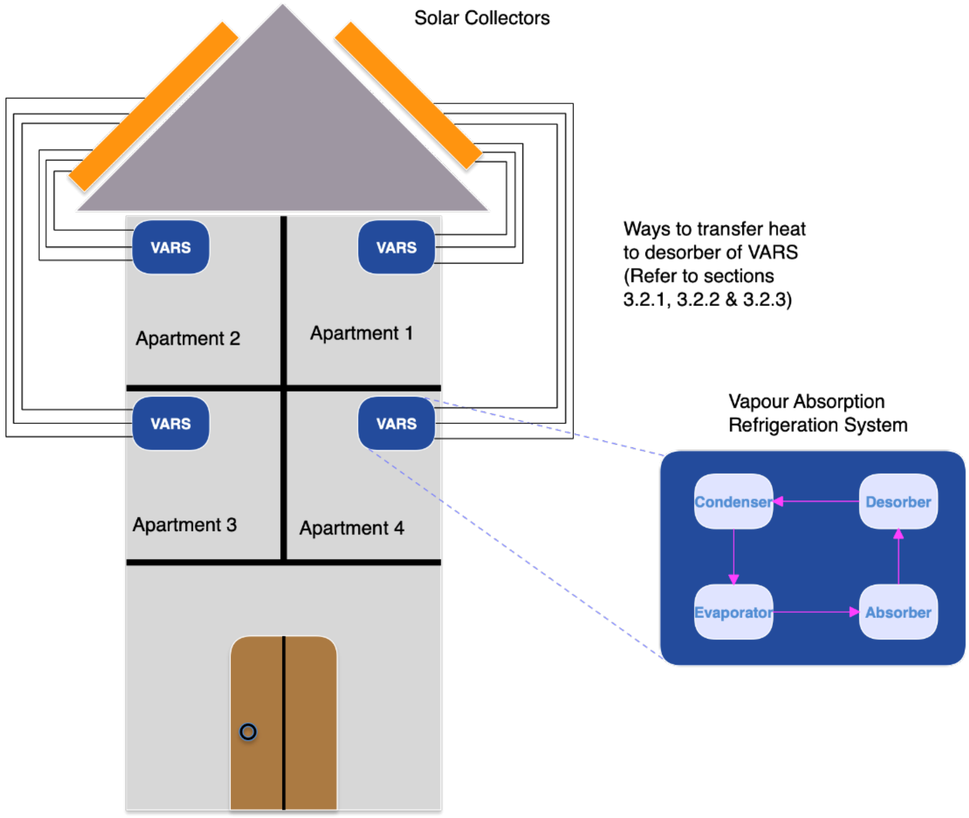

Figure 12: Solar Heat Driven VARS for one building

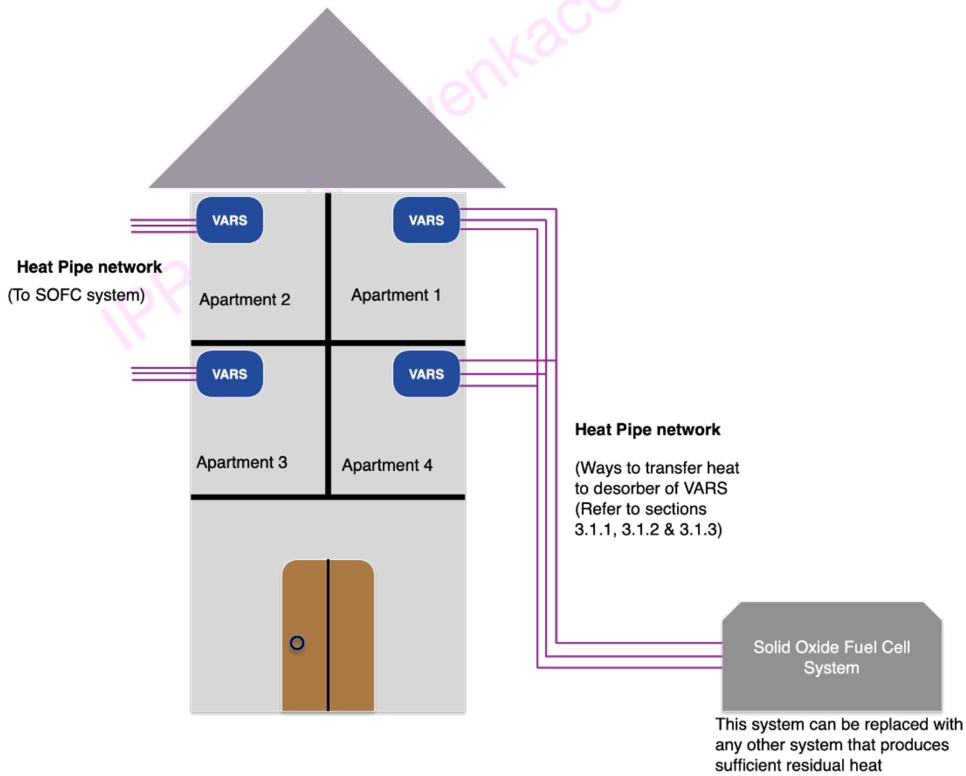

Figure 13: VARS coupled with Solid Oxide Fuel Cells

4.3 VARS using residual or renewable heat – Multiple apartment building

It can very often be the case that in many developing countries (under the category of 'hot and tropical climate') most of the buildings do not have any sources of renewable or residual heat integrated or built into the structure. Also, for newer buildings, if the latest building standards and codes were not followed then they too have no provision for tapping residual/renewable heat. In this case, how can thermally driven cooling systems be installed in these apartments? Or the main question is how to get the necessary amount of thermal energy to the individual VAR unit installed in these buildings if the customers bought one?

One way to do this is to have a centralised location for each neighbourhood which can generate both renewable and residual heat and then transferring this thermal energy via a suitable heat transfer fluid to each of the apartment buildings. The heat transfer fluid supplied to each of the buildings should have sufficient heat and temperature levels needed to drive the combined heat load of all desorbers of the VAR units in that building. For e.g. the centralised location can use advanced solar collectors which can generate heat at a higher temperature and then transfer this to an HTF or the centralised location can have a larger biogas driven SOFC generator and then transfer the residual heat to the HTF or it can use a combination of both renewable and residual heat in transferring heat to the HTF which is ultimately distributed to the buildings. It is envisaged that this is a more effective and practical approach rather than a district cooling system where chilled water at 10 °C is supplied to buildings. For reasons mentioned in the introductory part of the chapter, circulating chilled water via suitable conduits inside a space may not produce the desired cooling effect needed for thermal comfort. A diagrammatic representation of this concept is presented in Figure 14.

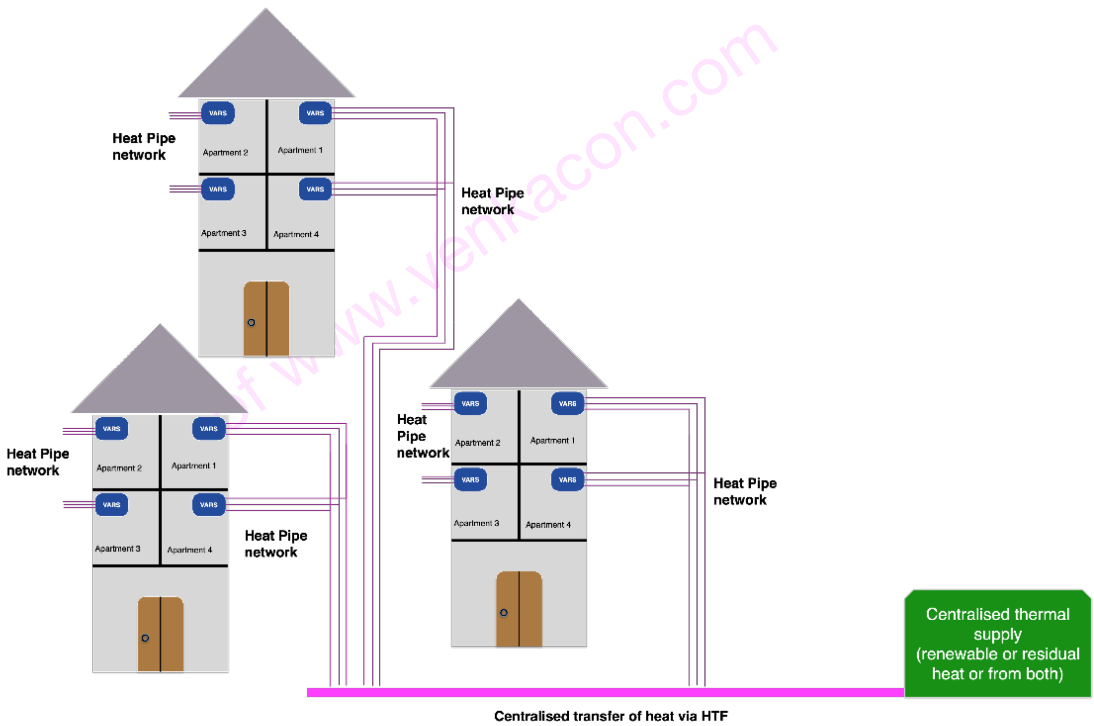

Figure 14: VARS using residual or renewable heat – Centralised supply

4.3 Design of heat pipe heat exchangers and heat transfer solutions

One of the important aspects in heat driven cooling systems is the availability of heat in ample quantities and at the temperature needed to run the thermally driven cooling system. As heat pipes are an effective and efficient link between sources of heat (both renewable and residual) and sink, it is quintessential to look at some of the designs and configurations that the heat pipe heat exchangers must have in order to accomplish this task. In order to make heat driven cooling systems a reality, heat pipe heat exchangers or heat pipe networks are needed at the following areas:

a. At the desorber
b. Between SOFC stack/system and heat transfer fluid
c. Between SOFC stack/system and desorber
d. Between solar collector and desorber
e. Between heat transfer fluid and desorber
f. At the condenser and absorber of the VARS
g. Between centralised heat transfer and individual apartments

Some designs on how these heat transfer networks must look is given in Figure 15 (absorber integrated with heat pipes), Figure 16 (between centralised heat transfer fluid and desorber of individual VARS), and Figure 17 (at multiple locations in a complete system).

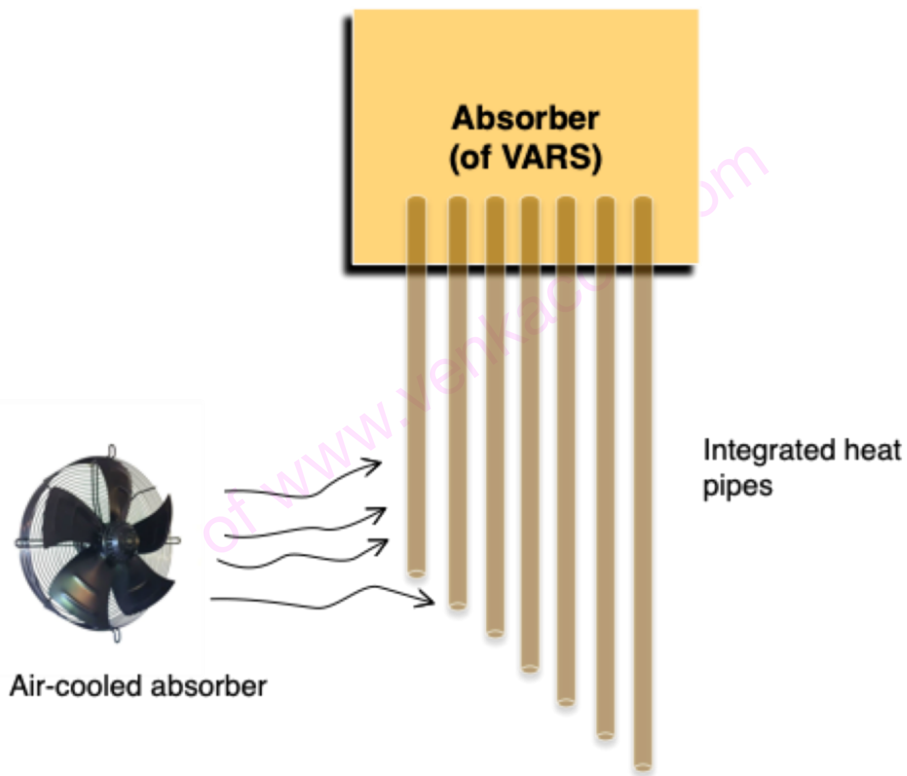

Figure 15: Air cooled absorber with heat pipes

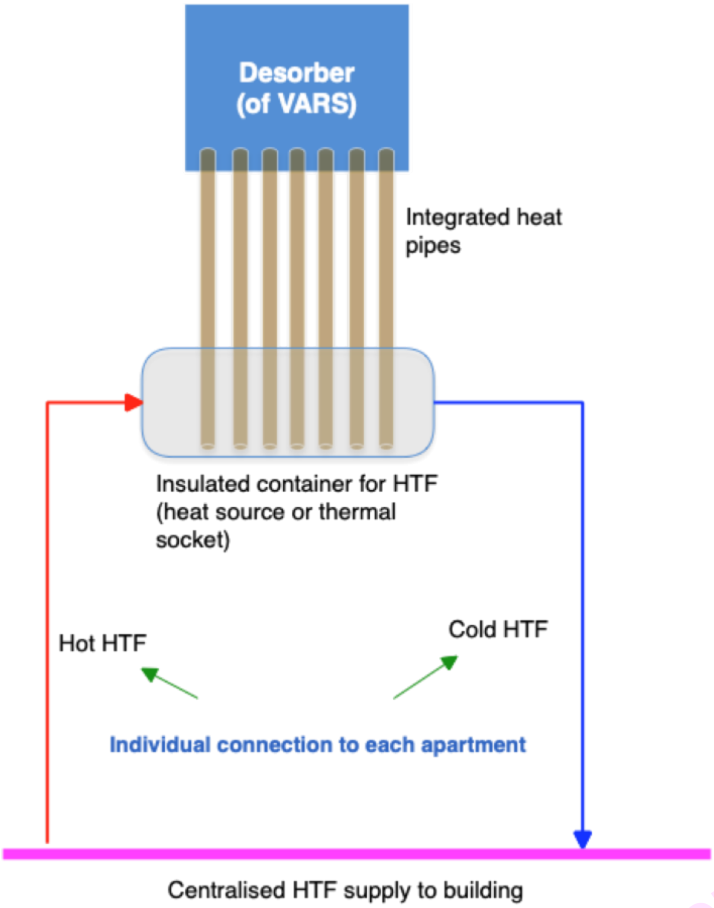

Figure 16: Heat Pipe heat exchanger connected to centralised heat transfer fluid

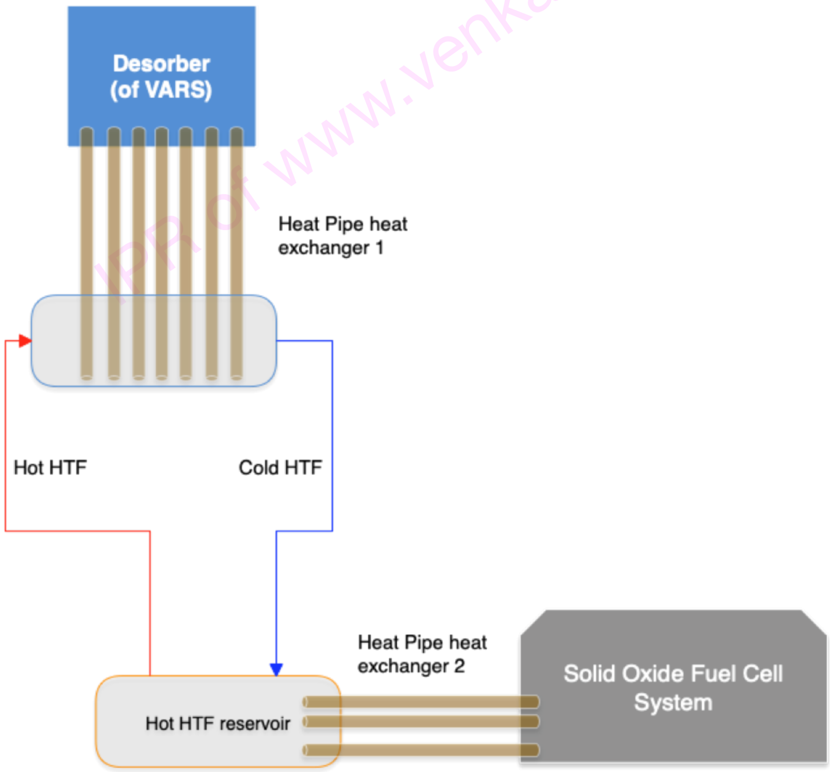

Figure 17: Heat Pipe Heat Exchanger at multiple locations in a system

Solar radiation is widely available in ample quantities in the countries that need air-conditioning systems for most part of the year and also the technology (solar thermal) for tapping this renewable heat is widely available. On the other hand, SOFC is a new technology and relatively expensive however together with biogas as a fuel, it is envisaged to play a greater role in the power generation market and when that happens systems for tapping heat must be readily available to make use of the high-quality residual heat. System designers and developers may use a combination of renewable and residual heat sources to supply the required quantity of heat and in doing so they will need to invent different designs of heat pipe based heat exchangers and networks besides the examples and figures shown above. Other advancements in micro-channel heat transfer are also expected to advance deployment of thermally driven cooling systems.

To make thermal driven cooling systems a reality, a *thermal socket*, akin to an electrical socket, must be made available to each apartment or house. What this thermal socket will do is provide the thermal energy needed when a small scale VARS is installed at the apartment/house.

Note: The term *thermal socket* is coined and introduced for the first time in this report and also in the broad context of HVAC. This term needs to be expanded and defined further to elaborate its importance and this is out of the scope of this report. The readers are advised to contact the author for further details.

4.4 Methodology for system design & development

It is very well known that thermally driven cooling systems work but they are not widely implemented on a small scale. So, what can be done to implement them widely? There are a number of components that are involved in the thermally driven cooling system (VARS) that warrant detailed engineering calculations, simulation, design and manufacturing. This section provides an insight into which components and sub-systems need in-depth engineering and development and what key aspects need to be looked into. For reasons of brevity, detailed calculations are not presented, but only the methodology and approach are presented here. The reader can use these together with other standard textbooks in carrying out detailed calculations for each of the components.

i. Heat Source –

The most important driver that is going to make the VARS work is the availability of thermal energy. Having sufficient thermal energy in the right quantity and temperature levels is quintessential for the successful operation of VARS. Calculating this is quite straightforward. Data on renewable and residual heat available in different countries that fall under the category of 'hot and tropical' can easily be made available and checked if they are sufficient to drive a cooling system. The sizes of cooling units that these heat sources must cater to range from 0.75 ton of air-conditioning to 2 tons of air-conditioning. One ton of air conditioning is roughly able to cool down 12000 BTU of air per hour or providing 3.5 kWh of cooling. In the examples presented here, thermal energy from solar insolation for a particular building or area can easily be calculated and also the amount of thermal energy from a Solid Oxide Fuel Cell System can be calculated based on the size and operating conditions of the system. Calculations for other residual sources of heat can also be made and checked if the quantity and temperature of heat is sufficient to drive a VARS or group of VARS.

ii. Heat Transport –

The next important and vital link to this whole concept is the capture and transport of the generated heat. This is where heat pipes come into play. Once the quantity of heat to be transported is determined and the temperature of operation is established then the individual heat pipe and in turn the heat pipe heat exchanger can be designed to meet the application requirements. The reader is encouraged to read textbooks on heat pipes [15, 16] on how to go about choosing different aspects of heat pipe – type, outer material (container of heat pipe), working fluid, screen size, flow limitations etc.

Design and development of heat pipes for thermally driven cooling systems should be carried out for different types and sizes of cooling systems that one wants to have in their product portfolio. Some of the technical aspects that warrant attention are:

- Heat flux at the evaporator and condenser end of the heat pipe.
- Fluid flow aspects of the working fluid inside the heat pipe.
- Enhancing the surface area at the evaporator and condenser end of the heat pipes.
- Limitations on the length of the heat pipe with the heat transport capability.
- Thermal response of the heat pipe to fluctuating heat levels.

iii. VARS unit –

Once the heat source and the heat transport means have been identified and engineered, the next piece of the puzzle is to design, engineer and develop a compact VARS with a similar footprint to that of the VC system. The main components that warrant attention are as follows:

a. Desorber & absorber

The desorber and the absorber together act as the thermal compressor in a VAR system and take over the role of the electric compressor (in a VC system). It is at the desorber where the heat input takes place, and the refrigerant-absorbent solution boils off. Depending on the refrigerant-absorbent solution used and the cooling range desired, the mass flow rate of refrigerant needed for cooling must be calculated based on the amount of heat supplied. Along with the quantity of refrigerant generated, the quality of refrigerant generated must also be calculated. Desorber designs for incorporating heat pipes or the heat transfer fluid directly must be carried out coupled with fundamental physics processes such as two-phase flow, boiling and vapour flow dynamics. Along with fundamental studies, engineering of the desorber for materials, shape and structural robustness must also be carried out.

The absorber is the place where the refrigerant vapour coming from the evaporator is mixed with the weak solution coming from the desorber to regenerate the strong solution which is then pumped back to the desorber. The mixing process is exothermic and generates heat and this heat needs to be removed and heat pipes can play a vital role in compact absorber designs by instantly removing the heat generated from the mixing process and transferring it to the ambient. Similar to the desorber, the absorber also needs studies and analysis on fundamental physics processes such as mixing of vapour into liquid, flow dynamics and heat transfer.

b. Condenser & Evaporator

These two components are quite straightforward, and the designs can easily be taken and adapted from the VC system. The condenser is the place where the refrigerant loses heat and turns to liquid, the heat being rejected to the ambient and the evaporator is the place where the heat from the space to be cooled is absorbed by the liquid refrigerant, turning it back to vapour. It would be preferred to have both these components air cooled in order to reduce the complexity of the VARS and to make its installation easy in households.

A sample flow chart for the design of a directly coupled SOFC-VAR system is given in Figure 18. Similar processes can be developed for integration with other sources of heat.

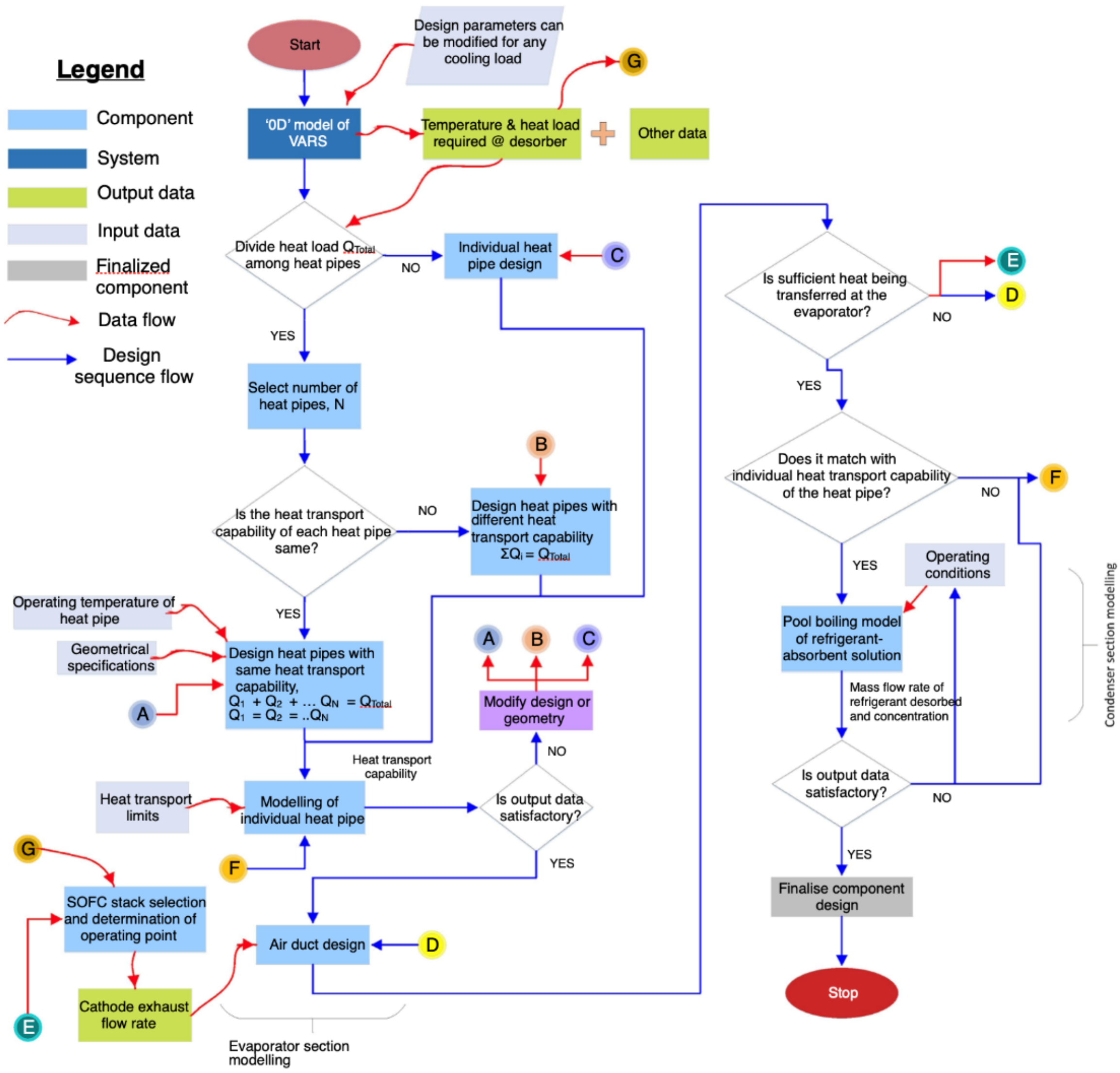

Figure 18: Flow Chart for design of directly coupled SOFC-VAR System [26]

iv. Control unit

A control unit is absolutely essential for smart and energy-efficient operation of the VARS. More control and sensor information will aid in better use of energy needed by the cooling system and also its operation. The control unit must be able to adjust and control the following:

a. The heat input needed at the desorber.
b. The refrigerant production rate at the desorber based on the cooling need at the evaporator.
c. The pumping speed of the solution pump, depending on the cooling need.
d. The concentration difference between strong and weak solution and its effect on energy efficiency.
e. Calculating the deficiency in heat input and communication with the heat source.

This is a topic that warrants special attention on its own and the possibilities and use cases are endless. The design of the VARS and its interaction with the heat sources are the main factors that affect the control strategy and in turn the design of the control unit.

v. Working fluids and heat transfer fluids

A number of working fluids can be used in heat pipes and a range of heat transfer fluids can be used for transferring heat from the source to the heat pipe. Of course, it goes without saying that one must strive for using fluids that are environmentally friendly. Particular attention must be paid to the heat transport capability of these fluids, their degradation during the course of cyclic operation, their compatibility with materials that they will come in contact with, and the flow dynamics needed.

With the above-mentioned methodology together with advanced engineering and development, it is indeed possible to design and operate a cooling system that is driven by thermal energy and that can work in a continuous manner.

5. Energy savings

The hypothesis that we have been working with throughout this entire report is that a system which is able to operate and run on residual or renewable thermal energy wherever and whenever possible will definitely bring down the primary electrical energy needs.

Let us look at the amount of energy needed to run a conventional air-conditioner (based on VC technology) and compare it with the energy needs of an air-conditioner based on VARS technology. Air-conditioners are usually categorised in 'tons' for the amount of air they are able to cool. Most common household air-conditioners range between 0.75 and 2 tons [27, 28], the corresponding cooling power for the respective tonnage is shown in Table 2.

Ton	Cooling Power (kWh)
0.75	2.637
1.0	3.516
1.5	5.275
2.0	7.033

Table 2: Tonnage of Household Air Conditioner [27]

This means a 1 ton air-conditioner is able to provide roughly 3.5 kW of cooling per hour. Based on the air-conditioners available in the market, the split ACs are more energy efficient than window ACs, resulting in lower energy consumption and both types are based on vapour compression technology. Figure 19 shows the average electrical energy consumption of window and split ACs and compares it to a small-scale VARS. The values shown in this graph correspond to the window and split ACs achieving a room temperature between 18 and 24 ^{o}C and the small scale VARS achieving a room temperature of –20 ^{o}C. It is to be emphasised that lower is the need for the temperature of the room to be higher is the energy needed for running the compressor of the air-conditioning unit (based on VC system). Hence here, we are comparing the operational scenario for VARS under extreme conditions with that of the VC unit under milder operating conditions. What we see here is that the electrical energy consumption of the VARS is roughly 4.5 % to that of the VC system when the VARS is operating under extreme conditions and this number is bound to be even lower if the VARS was operating for temperatures between 18 and 24 ^{o}C. The major electrical energy consuming component of VARS is the solution pump and the number presented in the graph corresponds to the electrical needs of the solution pump. Even if we add a few fans (for air cooled condenser & absorber and a fan for the evaporator to blow air on the evaporator coils) and some electronics to the VARS, the electrical energy consumption is not expected to exceed 15% that of the VC system.

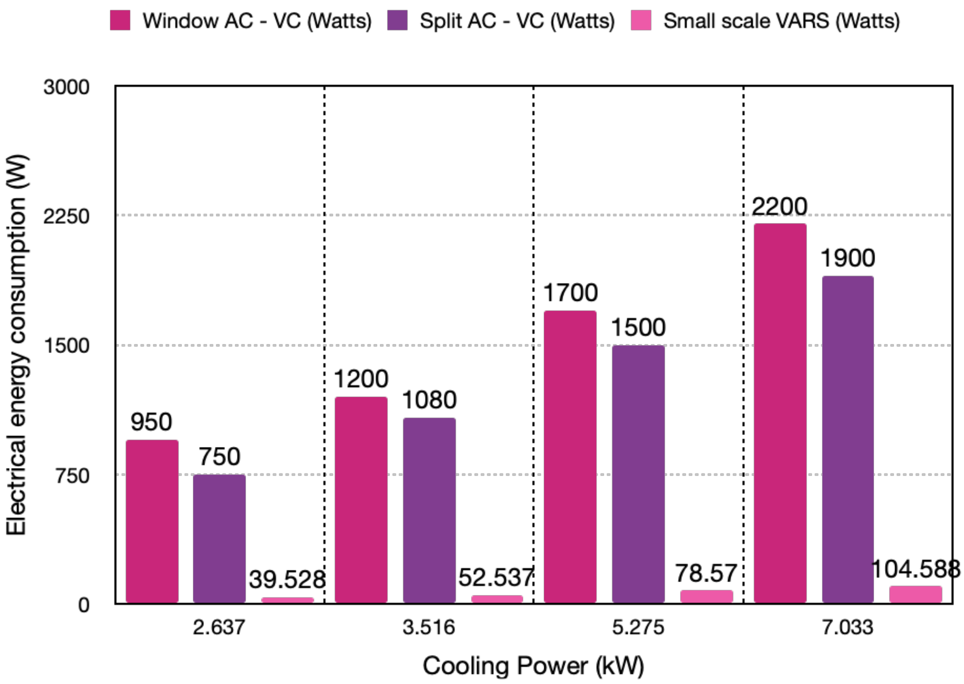

Figure 19: Electrical Energy Consumption of VC vs VARS Cooling system

So, what this means is there is tremendous scope somewhere in the range between 85 and 95% for electrical energy reduction if thermally driven cooling systems were made widely available for home air-conditioning. From the graph in Figure 19, if we take a 1-ton air-conditioner which provides 3.5 kW of cooling per hour and if this air-conditioner is thermally driven, then it consumes just 52.5 W per hour as compared to 1200 W with a VC based unit. If one multiplies this with the total number of air-conditioners in a country (hot & tropical) then the amount of electricity savings is tremendous.

It will be good to get a complete view on the energy needs of the VARS as what was presented above is just the electrical energy needs. Table 3 summarises the total energy needs for both types of cooling systems for 1 ton of air conditioning. Units running on VARS technology have a coefficient of performance (COP) of just 0.8 as compared to units running on VC technology which have a COP of roughly 3. Now that makes them relatively inefficient however the advantage is they run on free thermal energy. The VARS needs a total energy of 4.452 kWh out of which 4.4 kWh is from thermal energy which is tapped for free and made use of.

	Vapour compression system	Vapour Absorption system	Remarks
Cooling power generated (kWh)	3.515	3.515	Cooling power achieved per hour
Electricity consumed (kWh)	1.2	0.052	This is the electrical energy requirement
Thermal energy needed (kWh)	--	4.4	This energy is assumed to be free – either renewable heat or residual heat
COP	3	0.8	

Table 3: Theoretical values of energy needs for an AC unit based on VC and VARS technology

How does the savings or reduction in electrical energy translate to savings or reduction in CO_2 emissions? This is quite straight forward to determine. Based on what the source of the electricity is for a particular area or province or country, the related CO2 emissions from that process or method of electricity generation is well known or can be calculated. This kind of data quantified as grams carbon dioxide-equivalent emitted per kWh of electricity generated can also be obtained from [29]. Hence, every kWh of electricity that can be saved, either by increased efficiency or other means, the need for its generation can be reduced and therefore directly the amount of CO_2 generated. However, one must keep in mind that this applies only when the method of electricity generation is not 100% from renewables because if the electricity generated is totally from renewables, then there are no CO_2 emissions but even in that case the saved electrical energy can be used for other purposes as mentioned earlier in the chapter. The reader must keep in mind that these are just the direct emissions coming out of the process of electricity generation and not the lifecycle emissions which will warrant a detailed life cycle analysis (LCA).

Conclusions & Future outlook

There is a direct correlation between ambient temperature and space cooling energy needs. The higher the ambient temperature, the greater is the need for space cooling and therefore higher is the energy need for running the cooling system. Thermally driven space cooling and refrigeration systems have a huge market potential provided the system and the unit is developed to a size and scale that can compete with the current vapour compression based systems in terms of bulkiness and ease of installation. The thermal compressor (desorber plus absorber) in a small scale VARS must have a volume footprint similar to that of the electrical compressor in a VC system in order to act as a contender to replace it and this is absolutely key in widespread adoption of VARS.

As cooling takes up 20% of the total electricity demand in buildings and other places, replacing the total energy demand for cooling with freely available residual or renewable thermal energy will go a long way in reducing the energy needs from cooling. As we have seen, there is scope for reducing electrical energy requirement anywhere in the range between 85 and 95% when implementing thermal driven cooling systems. For e.g. even if a modest 10 % of the cooling needs can be met by using thermal energy and not electrical energy, then the available electricity can be put to use for other purposes as the demand for electrical energy keeps rising every year. Electrical energy has high quality exergy and should be used for applications that absolutely warrant it.

It was elaborated in this report that two vital aspects crucial to make thermally driven cooling systems work are the availability of thermal energy in sufficient quantities and the transport of this thermal energy (heat) to the thermally driven cooling system. The former is available in copious amounts in 'hot and tropical countries' in the form of solar energy while the latter is enabled by the use of heat pipes and heat pipe heat exchanger networks. These two aspects will solve more than 50% of the technical challenge in making thermal driven cooling systems a reality. The ways and means to tap and transfer residual and renewable heat were detailed out in sections 3.1 and 3.2 and the role that heat pipe heat exchangers will play in the broader context were detailed out in section 4.3. There is immense scope for making thermally driven cooling systems a reality with technology advancement in the areas of heat pipes and desorbers.

The ultimate goal for we as a society should be to be able to provide affordable space cooling solutions to people and countries who simply cannot afford buying expensive technology and this must be done by using renewable and residual heat as much as possible. Just like how heating is essential to live and work comfortably in cold countries, the same is true for cooling in hot and humid countries. A lot of people in the developing world which fall under the category of 'Hot and humid' tolerate the extreme heat every single day solely for the reason that they just cannot afford to buy the system and even if they can buy it cannot afford to pay the huge operating costs that tag along with it.

One may argue that if there is sufficient renewable electricity generation for all needs and demands (which will definitely be in the future after 2050) then one can simply use the conventional air-conditioning units based on VC technology. But the counter argument will be why not develop units and systems that are able to run on free thermal energy and reduce the dependence on electricity (or electrical energy). Technology wise if both are possible then systems running on residual thermal energy will ensure that electrical energy can be directed to other purposes such as EV charging, energy storage or hydrogen production or any other new application(s) that may get invented in the coming decades etc.

Designing a working unit for different tons of air conditioning and providing appropriate thermal interfaces (the *thermal socket*) with thermal specifications (temperature, heat flow etc.) will instil confidence in the minds of end users and policy makers alike. This way units can be installed anywhere, and the thermal source can be flexible.

People have preferences and this is true for any technology, some may want electrically driven cooling systems and some may want thermally driven cooling systems. It is like some people wanting solar panels installed on their roof in order to reduce their operating costs through a certain time period and being sustainable whereas some prefer to use grid electricity and wait till the grid is decarbonised. Same goes for thermally driven cooling systems. Some people will be fascinated by the idea of minimising operating costs of their cooling system and will be the first up takers while some may still stick with the proven electrically driven air-conditioners. But whatever be the case, if one is able to make a system work in an alternate way with free or residual energy then people will see the value and benefit in it and will be more than open and willing to make the change and this is what thermally driven cooling systems are expected to do.

Of course, there will be challenges that need to be solved but the first step is to be proactive and find an initial project where such a system can be implemented and demonstrated.

Appendices and Nomenclature

AC – Air Conditioner
CHP – Combined Heat and Power
COP – Coefficient of Performance
EV – Electric Vehicle
GHG – Green House Gas
HTF – Heat Transfer Fluid
HVAC – Heating Ventilation and Air Conditioning
LCA – Life Cycle Analysis
SOFC – Solid Oxide Fuel Cell
VARS – Vapour Absorption Refrigeration System
VC – Vapour Compression

Disclaimer:

References

[1] The Future of Cooling – Opportunities for energy efficient air conditioning, Report by International Energy Agency, 2018

[2] Ding Y, Guo Q, Guo W, Chu W, and Wang Q: Review of recent applications of heat pipe heat exchanger use for waste heat recovery. Energies 2024;17, 2504. DOI: https://doi.org/10.3390/en17112504

[3] Circulating chilled water through the existing central heating system [Internet]. Available from: https://www.theguardian.com/notesandqueries/query/0,5753,-24934,00.html#:~:text=SPECULATIVE%20SCIENCE-,In%20hot%20weather%2C%20would%20it%20be%20possible%20to%20cool%20the,the%20exisiting%20central%20heating%20system%3F&text=Yes%2C%20but%20it%20wouldn't,radiators%20and%20the%20surrounding%20air [Accessed: 2024-07-20]

[4] The cooling dilemma amid climate change [Internet]. Available from: https://www.unicef.org/innocenti/cooling-dilemma-amid-climate-change [Accessed: 2024-07-19]

[5] Writer JW. What is sustainable cooling and how can it help tackle the climate crisis? [Internet]. 2023. Available from: https://climatechampions.unfccc.int/what-is-sustainable-cooling-and-how-can-it-help-tackle-the-climate-crisis/ [Accessed: 2024-07-19]

[6] Solid oxide stacks for fuel cell systems [Internet]. Available from: https://elcogen.com/products/solid-oxide-stacks-for-fuel-cell-systems/ [Accessed: 2024-07-19]

[7] Solid Oxide Technology [Internet]. Available from: https://www.ceres.tech/technology/ [Accessed: 2024-07-19]

[8] Solid Oxide Technology [Internet]. Available from: https://www.bloomenergy.com/technology/ [Accessed: 2024-07-19]

[9] Solid Oxide Fuel Cell [Internet]. Available from: https://en.wikipedia.org/wiki/Solid_oxide_fuel_cell [Accessed: 2024-07-19]

[10] What is biogas? [Internet]. Available from: https://www.nationalgrid.com/stories/energy-explained/what-is-biogas# [Accessed: 2024-07-20]

[11] Langnickel H, Rautanen M, et al. Efficiency analysis of 50 kWe SOFC systems fueled with biogas from waste water. Journal of Power Sources Advances. 2020; 2: 100009. DOI: https://doi.org/10.1016/j.powera.2020.100009

[12] Singhal S. High Temperature Solid Oxide Fuel Cells – Fundamentals, Design and Applications. Elsevier; 2004. ISBN 1493303813, 9781493303816

[13] Performance of a LiBr water absorption chiller operating with plate heat exchangers [Internet]. Available from: https://e-archivo.uc3m.es/rest/api/core/bitstreams/42801bf9-3eb4-4e0f-8564-30d51effe2ab/content [Accessed: 2024-07-20]

[14] Herold KE, Rademacher R, Klein SA. Absorption Chillers and Heat Pumps. 2nd Edition: CRC Press; 2016. ISBN 9781498714341

[15] Silverstein CC. Design and technology of heat pipes for cooling and heat exchange. 1st Edition: CRC Press; 1992. ISBN 9780891168591

[16] Reay D, McGlen R, and Kew P. Heat Pipes – Theory, Design and Applications. 6th Edition: Elsevier; 2013. ISBN 9780080982663

[17] Solar Thermal Collector. ScienceDirect [Internet]. Available from: https://www.sciencedirect.com/topics/engineering/solar-thermal-collector#chapters-articles [Accessed: 2024-07-19]

[18] What is exactly solar thermal energy? [Internet]. 2016. Available from: https://www.bmwk-energiewende.de/EWD/Redaktion/EN/Newsletter/2016/20/Meldung/direkt-account.html [Accessed: 2024-07-19]

[19] Solar Explained, Solar Thermal Collectors [Internet]. 2024. Available from: https://www.eia.gov/energyexplained/solar/solar-thermal-collectors.php#:~:text=Non%2Dconcentrating%20solar%20collectors&text=A%20flat%20metal%20plate%20that,absorber%20to%20reduce%20heat%20loss [Accessed: 2024-07-19]

[20] Copper tank solar water heater [Internet]. Available from: https://www.indiamart.com/proddetail/100lpd-solar-water-heater-16953394255.html [Accessed: 2024-07-19]

[21] Platzer W, Stieglitz R. Solar Thermal Energy Systems – Fundamentals, Technology, Applications. Springer Cham; 2024. ISBN 9783031431722

[22] Online calculation tool for solar thermal system [Internet]. Available from: https://online.tsol.de/en/ [Accessed: 2024-07-20]

[23] Venkataraman V. Thermal modelling and coupling of a heat pipe integrated desorber with a Solid Oxide Fuel Cell. Applied Thermal Engineering. 2019; 147: 943-961. DOI: https://doi.org/10.1016/j.applthermaleng.2018.10.131

[24] List of cities by sunshine duration [Internet]. Available from: https://en.wikipedia.org/wiki/List_of_cities_by_sunshine_duration [Accessed: 2024-07-20]

[25] Diesel generator fuel consumption guide [Internet]. Available from: https://www.bluedm.com.au/blog/diesel-generator-fuel-consumption-guide-/#:~:text=heavy%20duty%20use.-,The%20efficiency%20of%20diesel%20generators%20is%20expressed%20as%20their%20fuel,for%20your%20power%20requirements%20here. [Accessed: 2024-07-20]

[26] Venkataraman V. Coupling of a Solid Oxide Fuel Cell with a Vapour Absorption Refrigeration System for refrigerated truck application [thesis]. University of Birmingham, UK; 2017

[27] Window AC vs Split AC Energy consumption [Internet]. 2024. Available from: https://www.acsize.com/window-ac-and-split-ac-energy-consumption/ [Accessed: 2024-07-20]

[28] How much does air-conditioning cost to run? [Internet]. 2023. Available from: https://www.climamarket.eu/blog/en/how-much-does-air-conditioning-cost-to-run/ [Accessed: 2024-07-20]

[29] Carbon intensity of electricity generation [Internet]. 2024. Available from: https://ourworldindata.org/grapher/carbon-intensity-electricity?time=1996 [Accessed: 2024-07-20]