Effective Utilization of Waste Heat in Fuel Cell Stack

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Abstract- In the rapid transition of mobility sector from the internal combustion engines to electric mobility, two main ways in achieving this change are battery powered electric vehicles and fuel cell electric vehicles. While both have their respective merits and demerits, this paper mainly focuses on fuel cell electric vehicle in the aspect of heat energy transfer from fuel cell to vehicle interior to keep it warm. One of the perks the FCEV has is its heat energy liberated while in operation but this is not the case in BEV. the heat thus liberated in fuel cell can be recovered and used to heat up the vehicle interior. So, in this context this paper deals only with the heating but not the cooling in the climatic control inside the vehicle. In most cold countries heating is mainly considered than the cooling. In order to understand whether the heat energy generated by fuel cell is sufficient to keep the vehicle interior warm, it is required to understand the heat energy consumed by the vehicle and also amount of heat energy liberated in the fuel cell. So, this paper gives you insights over these concepts in addition a transfer mechanism is designed for the heat transfer from fuel cell to interior of the vehicle. Viewers are advised to refer another textbook of thermodynamics to clearly understand the concept of heat energy liberated in the fuel cell

Indexed Terms- Fuel cell Electric vehicle, Heat energy, Battery electric vehicle, Vehicle interior heating, Utilization of waste heat.

I. INTRODUCTION

The two main types of electric vehicles are FCEV and BEV, the energy required for the motion of battery powered electric vehicle is drawn from the battery which is often required to be charged by an external power supply. In contrast to this a FCEV generates the energy required by using the fuel cell stack which eliminates the concept of charging often. Both the types of vehicles have their pros and cons, but in this paper heat management system typically vehicle interior heating is only concentrated, in colder countries where the temperature is below 10°C keeping the interior of vehicle warm is of more interest to stay comfortable. In conventional internal combustion engine vehicles, some of the heat for interior heating is taken from the ICE engine but most of it comes from the other heating techniques like resistive heating., but in the electric vehicles especially BEV energy consumed for heating is only taken from the battery making energy consumption more and it also decreases the range of the vehicle which is not desirable. To overcome this problem a basic concept in fuel cell which comes from the fact that a fuel cell is an electrochemical device which converts the chemical energy into useful electric energy and waste heat, this waste heat generated is used for the heating purposes. To understand clearly the concept of amount of heat generated in fuel cell, it is required to have knowledge regarding it.

As said earlier, fuel cell is an electrochemical cell just like the battery which consists of an anode and cathode. near anode oxidation takes place and at cathode reduction process takes place. The electrons liberated at anode are driven to the load through an external circuit and protons are driven to the cathode giving out the products. There are various types of fuel cells which are operating at different temperature ranges. some of them are given below

- Phosphoric acid fuel cell (PAFC)
- Polymer electrolyte membrane fuel cell (PEMFC)
- Alkaline fuel cell (AFC)
- Solid oxide fuel cell (SOFC)

The operating temperatures and type of electrolyte used in these fuel cells are tabulated below

Type of stack	Operating temperature	Electrolyte used	Catalyst	Charge carriers

PEM FC	60°C-80°C	Polymer membrane	Platinum(pt)	H^+
PAF C	200°C	H_3PO_4(liquid)	Pt	H^+
AFC	60°C-220°C	Liquid KOH	Pt	OH^-
MC FC	650°C	Molten carbonate	Ni	CO_3^{2-}
SOF C	600°C-1000°C	Ceramic	Perovskites(ceramic)	O^{2-}

for illustration process, we take the example of low temperature PEMFC in this paper. Moreover, most of the automobile applications are also based on this type of fuel cells for their benefits of low operating temperatures.

A proton exchange membrane fuel cell (PEMFC) consists of anode where the oxidation of hydrogen takes place and at cathode protons H^+ ions react with oxygen to form water (no harmful emissions), when a hydrogen enters fuel cell through anode, it passes through gas diffusion layer GDL which consists of catalyst platinum pt, at this point the hydrogen splits into protons(H^+) and electrons. These electrons travel through the PEM which only allows protons and blocks the flow of electrons. At cathode the air (with 21% of O_2) is supplied, as a result the H^+ ions traveling through PEM react with oxygen forming water as a product. This can be more clearly understood the reactions given below

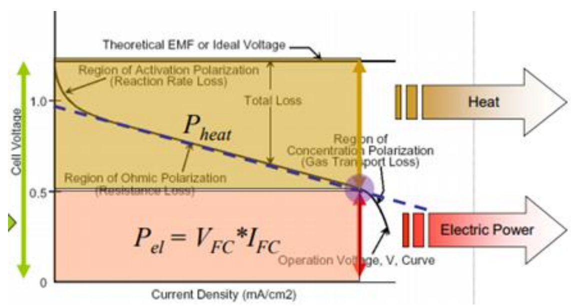
Anode reaction: $H_2 \rightarrow 2H^+ + 2e^-$
Cathode reaction: $2H^+ + (1/2)\ O_2 + 2e^- \rightarrow H_2O$
Overall reaction: $H_2 + (1/2)\ O_2 \rightarrow H_2O$

In this process of oxidation and reduction reaction, a voltage of 1.23V (LHV) or 1.418 (HHV) is maintained in a fuel cell (this could be more clearly understood in the following sections of this paper).

Along with this electrical power and heat energy is also liberated in fuel cell due to some losses. These losses can be broadly classified as

1. Activation and polarization losses
2. Ohmic losses
3. Mass transport losses

As these losses' magnitude increases the heat energy liberated will also increase thus by decreasing the electrical energy This is due to the first law of thermodynamics. To maintain thermodynamic equilibrium the energy which is supplied to fuel cell (Chemical energy) needs to be same with the energy coming out of the fuel cell (Electrical energy and Heat energy). As a result, as the losses increase it makes the heat energy generation more thus by decreasing the electrical energy. But in fuel cell electrical energy is often more interest than heat energy. Conventionally heat energy is dissipated by employing the cooling techniques which consumes the energy. The main problem arises here which requires energy for cooling making the fuel cell less attractive. To solve this problem, it is of great interest to use this heat to warm up the vehicle interior thereby reducing the energy consumed reduction for cooling the stack and also reducing the energy consumed by heater to heat up the vehicle. The V-I curve of fuel cell explains the losses, electricity generation and the heat produced very clearly.



Graph: V-I characteristics of fuel cell

From the graph it is clear that as point of operation of fuel cell moves down the curve the heat energy generation increases and electricity decreases signifying the losses in system. The main idea of this paper is to use that heat energy more effectively thus making the fuel cell electric vehicle more attractive than the battery powered electric vehicle.

In convention, the energy from the battery is used for heating the vehicle interior in battery powered vehicles which had adverse effect on the vehicle range. By employing the fuel cell electric vehicle, this energy can be reduced by using the heat energy from the fuel cell stack to heat up the vehicle interior which reduces the heater consumption. Please note that the energy consumed by the heater can only be reduced but not made to zero because at starting of the vehicle, the fuel cell doesn't generate energy and to be warm inside the vehicle heater will consume the energy till the operation of fuel cell.

II. ENERGY CONSUMPTION FOR HEATING AND COOLING INSIDE EV

To accomplish the goal of heating the vehicle interior from the heat generated by the fuel cell, it is very important to know the energy consumed by an electric vehicle for heating process. It also helps in understanding whether the heat energy from fuel cell is sufficient or not and related calculations. The heat energy liberated in fuel cell is discussed in next section and by comparing the heat energy consumed by EV and heat energy liberated in fuel cell we can be in a position to say whether the target of heat transfer is possible or not.

Although there are no standard calculations to estimate the energy consumed by heater or cooler or any other auxiliary devices like defroster, head lamps, heated wipers, nozzles., I think the better way to estimate this energy consumption is to consider it as a battery powered electric vehicle and compare it with fuel cell electric vehicle. To understand these calculations, we should be aware of the specific energy consumption of auxiliary devices

$E_{Aux} = E_{CC} + E_L + E_{WCS} + E_{O.S}$

Here
E_{CC} is the energy consumed for climatic control (heating or cooling), E_L is energy consumed by lights and horns, E_{WCS} is energy consumed by windows cleaning systems, $E_{O.S}$ is the energy consumed by other systems like radio, power steering and all other systems.

However, as heating the vehicle interior is our main motto in this paper. We limit ourselves by calculating the energy consumed for climatic control (E_{CC}). but by using the process followed below we may also be in a position to estimate the other energy consumptions. To achieve this, consider the following formula

$$De = (SOCmax - SOCmin) \times Tb \div Ce$$

Here
De is the depth of discharge of the battery in %, Tb is the total battery capacity in KWh, Ce is the energy consumption expressed in KWh/Km, SOCmax is the maximum of state of charge of the battery while SOCmin is the minimum state of charge.

The depth of discharge for a battery is simply the change in charge relative to when it is full, Tb is the total value of battery capacity expressed In KWh, Ce is the energy consumption of vehicle in our case this has to be calculated for good estimation. SOC is the state of charge and can be defined as the available capacity expressed as percentage of some reference, the reference sometimes could be its rated capacity but more generally we consider its current capacity at the last charge-discharge cycle. It is useful in knowing the amount of energy capacity left in a battery compared with the energy left in battery when it was new and gives us a good indication of how long a battery will continue to perform before it actually needs charging

There are several methods to estimate the state of charge for a batter, given below are some of them

1. Direct measurement: it uses the battery properties such as voltage and impedance to estimate it
2. Book keeping estimation: this method uses the discharging current and integrates over time for approximation of state of charge.
3. Adaptive systems: these adaptive systems are self-designing and can automatically adjust the soc for different discharging conditions.
4. Hybrid methods: these hybrid methods generally produce good estimation of state of charge for a battery when compared with the individual methods

To calculate the consumption of heater, we need to know the values of state of charge(max) and min value, total battery capacity for an electric vehicle when heater is on and in the similar way, we can also calculate it for the cooler

$$Ce = (SOCmax - SOCmin) \times Tb \div De$$

And to calculate the separate of consumption of heater and cooler, we need to know the values of energy consumption when both are turned off (Ce)

a.) Energy consumption of heater for heating the vehicle interior:

Firstly, we collect the values of total battery capacity Tb in KWh of the vehicle we need to calculate along with value of state of charge for the battery both maximum and minimum values.

Initially, we determine the depth of discharge when both heater/cooler is turned off , say X KWh/Km so the energy consumption in this case would be

$$Ceoff = (SOCmax - SOCmin) \times Tb \div X \quad \text{KWh}$$

And now we turn on the heater to calculate energy consumption(Ceheater on), let the depth of discharge when heater is on say Y KWh/Km.

$$Ceheater\ on = (SOCmax - SOCmin) \times Tb \div Y \quad \text{KWh}$$

To obtain the energy consumed by heater,

Ceheater = Ceoff - Ceheater on

And in the similar way we can estimate the energy consumption of cooler when we know the values of state of charge , total battery capacity of given electric vehicle.

However, the external temperature has a very significant impact on vehicle internal temperature that is in cold countries where external temperature is low(<10°c) in these areas heating is preferred and areas where external temperature is high(>30°c) cooling effect is preferred. Moreover whether it may be cooling or heating, external temperature plays a very crucial role in energy consumption of climatic control inside the vehicle.

In the case where heating is preferred, where there is a much difference between external temperature and internal temperature [internal temperature is generally considered as optimal temperature or room temperature typically in the range(20°c - 25°c)] the energy consumption also increases leading to decrease in the vehicle range and same is the case for cooling effect. This shows that energy consumption is directly related to the difference in external temperature(Te) and internal temperature(Ti)

Ce α (Te – Ti)

It is obvious that as energy consumed by heater increases, the range of vehicle decreases but how does it vary, the following example makes it clear.

Consider the energy consumed of an EV when both the heater/cooler is off as (Ceoff) as 210 KWh/Km and when the heater is turned on (please assume that external temperature as 8°c and desired internal temperature to be 22°c) energy consumption(Ceheater on) spikes to 230 KWh/Km and the vehicle range when both heater/cooler is off is estimated to be 423 Km. in this context estimation of energy consumed by heater , due to this consumption there is a decrease in the vehicle range is given below(here for a given electric vehicle, state of charge for the battery is estimated to be 80% as the maximum value and 20% as the minimum value).

Energy consumed by the heater with the given condition can be estimated as the difference as Ceoff and Ceheater on .

The percentage of battery used for heater $= (Ceoff - Ceheateron) \div Ceoff \times 100\%$

$$= \frac{(230-210)}{210} * 100\%$$
$$= 9.5\%$$

Vehicle range for the battery consumed for heater

= 423*90.5/100

= 383 Km

The decrease in vehicle range = 423 – 383 km.

= 40 Km

So there is an 40 km range decrease when a heater(with external temperature as 8°c and internal temperature as 22°c) is turned on for a full range of 423 Km. and when the Tb is given for a vehicle, and we can calculate Ceheater on (if not given) by the formula discussed above.

In the similar way , energy consumption Ce can be calculated for heater or cooler at any internal temperature and external temperature just by having the battery specifications of Tb, state of charge. However the approximation of energy consumption is not that accurate but this method is suitable for any kind of electric vehicle and this approximated value is pretty enough to decide whether the heat energy generated inside the fuel cell is sufficient for the heating the vehicle interior.

III. HEAT ENERGY LIBERATED INSIDE THE FUE CELL

The following section includes the calculation of heat energy that is liberated in fuel cell, along with this you will also be in a position to identify the fuel cell thermodynamics and the electrical energy produced inside the fuel cell. To understand it clearly, viewers are advised to refer another thermodynamics text book.

So, starting from the first law of thermodynamics which is already stated, we can write the following equation.

$$P_{input} = P_{output}$$

In a fuel cell, P_{input} is the chemical power of a fuel cell and P_{output} is the combination of electrical power and heat power

So, $P_{chem} = P_{heat} + P_{el}$

$P_{heat} = P_{chem} - P_{el}$

The input chemical power can be estimated by the product of enthalpy of the respective fuel and the volume flow into the fuel cell.

$$P_{chem} = h*v$$

Now, the concept of enthalpy comes into play, according to thermodynamics enthalpy is the sum of the systems internal energy and the product of its pressure and volume.

$$h = u + p*v$$

The electrical power can be given simply by the product of voltage and the current. But to explain it clearly we consider the thermo dynamical definition rather than the electrical definition. According to thermodynamics, the electrical work inside any fuel is given by the negative of the Gibb's force energy.

$$W_{el} = -G$$

And to explain the Gibb's free energy inside a fuel cell, we consider the enthalpy, when we remove the energy provided by the environment from enthalpy, we get the Gibb's free energy.

$$G = h - T*S$$

Where S = entropy.

Now, the entropy (S) is the measure of any system's state of disorder randomness (or) uncertainly there are several definitions for it.

$P_{heat} = P_{chem} - P_{el}$

$P_{heat} = h * v - (- G)$

Here v is the volume flow fuel into fuel cell which can be estimated by

$V = i / n*F$

Where $i = Q / S$

Q/s = rate of flow of charge

So, $P_{heat} = h * (i / n*F) - (-G)$

(represent G as dG as it is change in Gibb's free energy)

$P_{heat} = ((h*i) / (n*F)) - (-dG)$

After having the basic understanding of these concepts of enthalpy and Gibb's free energy, it is necessary to derive it for practical fuel cells as enthalpy and Gibb's free energy are required to calculate the heat energy inside a fuel cell.

1. To calculate the enthalpy from a chemical reaction

Consider the following reaction, as we know that enthalpy in similar terms is the energy inside a system. In a chemical reaction energy can be obtained by subtracting energy of reactants from the energy of the products.

$$xA + yB \rightarrow eE + dD$$

The enthalpy change at standard temperature and pressure (1 pa, 25^0C) is given by

Δh^{STP} = [e h_f^{STP}[E] + d h_f^{STP}[D]] – [x h_f^{STP}[A] + y h_f^{STP}[B]]

Here h_f^{STP} is the formation enthalpy of the respective element at STP.

And in a similar way, we can also find the entropy for the given chemical reaction.

ΔS^{STP} = [e S_f^{STP}[E] + d S_f^{STP}[D]] – [x S_f^{STP}[A] + y S_f^{STP}[B]]

Here S_f^{STP} is the formation entropy of the respective element.

Generally, we measure these enthalpy and entropy values at STP because they vary with the change in temperature and pressure. The variation of enthalpy and entropy w.r.t temperature can be understood by the following expression.

$$h_T = h_f^{STP} + \int_{T0}^{T} H_P(T).dT$$

Here h_T is the enthalpy of temperature at T.
h_f^{STP} is the enthalpy at STP.
$H_P(T)$ is the heat capacity of a substance.

And $S_T = S_f^{STP} + \int_{T0}^{T} ([H_P(T)]/T).dT$

Here S_T is the entropy of temperature at T.
S_f^{STP} is the entropy at STP.
$H_P(T)$ is the heat capacity of a substance.

After having these values of enthalpy and entropy, we can obtain the Gibb's free energy as we know that

$$G = h - T*S$$

Expressing in molar quantities, this expression changes to

$$\Delta G^{STP} = \Delta h^{STP} - T*\Delta S^{STP}$$

voltage of fuel cell V = $-\Delta G/nF$

Where n is the no of electrons liberated in a fuel cell and F is the faradays constant.

After having all these values, we can directly calculate the heat energy for any fuel cell

$$P_{heat} = ((i*h) / (n*F)) - P_{el}$$

Here we need to multiply the chemical power expression with a 'λ' called stoic metric factor because of the fact that amount of fuel to be supplied to an fuel cell is be determined by the power demand and according to this demand fuel is supplied to fuel cell and this can be best estimated by this factor (λ).

$$P_{heat} = [((i*h) / (n*F))*\lambda - (v*i)]$$

where v= -dG/ (n*F)

$$P_{heat} = [((\lambda*h) / (n*F)) - v]*i$$

It is the expression for the heat energy released by the fuel cell. To have the practical understanding of the heat energy generation. Let us calculate it for a PEMFC which uses the hydrogen as a fuel to generate electrical energy along with the heat energy.

For a standard $H_2 - O_2$ PEM fuel cell, the chemical reaction is given by

$$H_2 + (1/2)\, O_2 \rightarrow H_2O \text{ (liquid)}$$

Here H_2O can be obtaining in both forms liquid and vapour, for both values enthalpy changes here we consider it for to make the calculations less complicated. Let us assume the fuel cell is operated at STP conditions.

i) Enthalpy for $H_2 - O_2$ fuel cell:

the enthalpy equation as described previously is applied to find the total enthalpy of PEMFC.

Δh_f^{STP} = [h_f^{STP} (H_2O liquid)] – [h_f^{STP}[H_2]] + (1/2) [h_f^{STP} [O_2]]

For now, h_f^{STP} (H_2O liquid) = -285.83 kJ/mol
Here –ve sign indicates that energy is liberated.
h_f^{STP}[H_2] = 0 kJ/mol
h_f^{STP}[O_2] = 0kJ/mol
so, Δh_f^{STP} = [-285.83] – [0 + (1/2)*0]
= -285.83 kJ/mol

ii) Entropy for $H_2 - O_2$ fuel cell:

similarly the entropy equation which is described earlier is used to calculate the entropy values of PEMFC.

S_f^{STP} = [S_f^{STP} (H_2O liquid)] – [S_f^{STP}[H_2]] + (1/2) [S_f^{STP} [O_2]]

Similarly, the entropy values can also be found at the same website.

S_f^{STP} (H_2O liquid) = 69.95 J/mol.k
S_f^{STP}[H_2] = 130.68 J/mol.k
S_f^{STP}[O_2] = 205 J/mol.k
Therefore,

$S_f^{STP} = [S_f^{STP} (H_2O \text{ liquid})] – [S_f^{STP}[H_2]] + (1/2) [S_f^{STP} [O_2]]$
$= 69.95 – [130.68 + ((1/2) *(205))]$
$=-163.23$ J/mol.k

iii) Gibb's free energy calculation of $H_2 – O_2$ fuel cell: Thus the total energy in a PEMFC is given by gibbs free energy and can be determined as follows for a PEMFC.

$\Delta G^{STP} = \Delta h^{STP} – T*\Delta S^{STP}$

Here as we calculated enthalpy and entropy at STP, we also must calculate Gibb's free energy at STP only.

$T = 273+25^0c = 298k$

$\Delta G^{STP} = -285.83$ kJ/mol – 298k * (-163.23) J/mol.k
= -285.83kJ/mol – (- 48642.54) J/mol
= -285.83kJ/mol + 48642.54 KJ/mol

$\Delta G^{STP} = 237.188$ kJ/mol

So, now by having all the values of enthalpy, entropy and Gibb's free energy, we can calculate the value of voltage, heat energy and electrical energy inside a fuel cell.

Voltage of fuel cell at STP (v) = $-\Delta G / (n*F)$
= - (- 237.188)/ (2* 96485 C/mol)

Here n is no. of electrons (n=2)

Since $H_2 \rightarrow 2H^+ + 2e^-$

F= 96485 C/mol

V_{STP} = (237.188 kJ/mol)/ (2* 96485 C/mol)

V_{STP} = (237.188 kJ/C) / 192970

V_{STP} = 1.22914 V

Now, we can calculate heat energy at this point of operation

$P_{heat} = [((\lambda*h^{STP}) / (n*F)) – v]*i$

Here assume $\lambda = 1$

P_{heat} = [((285.83*1) / (2*96485)) – 1.22914 V] *i

P_{heat} = [1.48 – 1.22914 V]*i

But in practical it (1.22914V) is not the case of a fuel cell, by assuming the losses we had discussed in introduction. Fuel cell operates basically at (0.7 – 0.8V). So, let us assume after considering all the losses a fuel cell operates at 0.7V and 10A of current for instance then the heat energy is calculated as

P_{heat} = (1.48V – 0.7V)* 10A
P_{heat} = 7.8W

And also the electrical power can be calculated as

P_{el} = V*I = 0.7V * 10A
P_{el} = 7W

So, please observe that in a fuel cell after considering the losses, it is a surprising fact that more heat energy is produced than the electrical power, conventionally we are using the fuel cell as a source for only taking the electric power but it produces more heat power than electrical power. So I think it will be very beneficial if we also use this heat energy rather than simply neglecting it.

IV. USAGE OF FUEL CELL HEAT ENERGY TO HEAT THE VEHICLE INTERIOR

As we know from the above section, fuel cells are only 40%-60% electrically efficient. The rest of the energy is dissipated as the heat energy. Now we are intended to recover that heat and transfer it to the vehicle interior. the heat energy from the fuel cell can be recovered by two methods

1.) By natural convection of air against the external surface area of the fuel cell stack:

In this method, the air is blown forcefully over the surface of the fuel cell stack to remove the heat with the help of blowers arranged at the surface of fuel cell stack. This method of heat transfer isn't effective as we know that heat on the surface is very less than the heat in the inner part of the stack. However, this method is cost effective and can be used for small powered applications. more generally it is used for the cooling the stack but it is not suitable for the heat transfer.

2.) By free or forced convection of air/ liquid through the flow fields:

This method is more efficient than the previous one, the transfer medium (air or liquid) is forced to flow through a specially imprinted flow fields in the bipolar plates. By flowing the air/liquid into the plates heat inside the fuel cell can be recovered and this recovered heat can be used for the vehicle interior heating (detailed overview is given in the next section)

The choice of air or liquid as a transfer medium is decided on base of several factors, some of them are given below

a.) By considering the volumetric heat capacity: volumetric capacity of transfer medium determines the amount of energy that a medium can recover from the system. when liquid is flown (say water), the volumetric capacity of water is $4.2 J/cm^3K$ and volumetric capacity of air approximately 0.0013

J/cm^{3}K. water is far better than the air when we consider this factor.

b.) By taking into account of fuel cell stack power, when fuel cell power rating is low. Then flow of air is better than the flow of air because for a low powered fuel cell stack, the heat energy produced is also low and when we consider to flow water it may take out the essential heat which is required for the operation of fuel cell stack

c.) Abundance: although, we know that air can be easily taken from the atmosphere but when we consider the recirculation method of using the exhaust water from the fuel cell stack. Water can also be easily available. However, for recirculation process we need a separate mechanism which also requires cooling again. As the exhaust water coming out of fuel cell stack have higher temperatures which is not that good to reuse this hot water as a transfer medium of heat recovery.

Moreover, when we consider the air with moisture content of more than 50%, it will be a good substitute for the water transfer medium. As the volumetric capacity of is higher with moisture content when compared with the air without the moisture content. This air with 50% moisture content is readily available in the colder climatic conditions where the temperature is below 10°c. the basic fact is that flow of water will only be possible for heating the buildings or similar applications, but for the space heating applications like the vehicle interior heating air is preferred as transfer medium despite of low volumetric heat capacity.

V. DESIGN OF HEAT TRANSFER MECHANISM

After having the basic knowledge of the amount of heat energy liberated in the fuel cell and methods to use that heat energy it is now of great interest to design a mechanism to transfer the heat energy from the fuel cell to vehicle interior. Now the main problem arises, as of now we know that fuel cell produces more heat energy than electrical energy but now please make it clear that there are some fuel cells like PEMFC which obviously produces more heat than electricity but at lower temperatures. To make it clear, understand the basic difference between the temperature and heat energy. the heat is described as the total kinetic energy of the particles in a substance in simpler terms it is the transfer of thermal energy between particles in a substance and it is measured in joules or watts. The temperature is the average kinetic energy of molecules inside a substance simply it refers to how hot or cold a substance is. so, the temperatures at which fuel cell produces heat energy are the operating temperatures of the respective fuel cell

As the temperatures of the fuel cell is more, more heat energy can be transferred to the vehicle interior. So, in this perspective SOFC which has highest operating temperatures (operating temperatures are given in section 1) will be good for heat transfer. However, this type of fuel cells is not suitable for mobility applications they are more suited for the stationary applications

From the second law of thermodynamics, it is stated that heat only flows from higher temperature object to the substance at lower temperatures. however, there should be some temperature gap between high temperature object and lower temperature object which varies for the substance we choose. To understand clearly consider a high temperature flowing liquid and lower temperature liquid flowing in a flow field and in opposite direction as shown in figure below

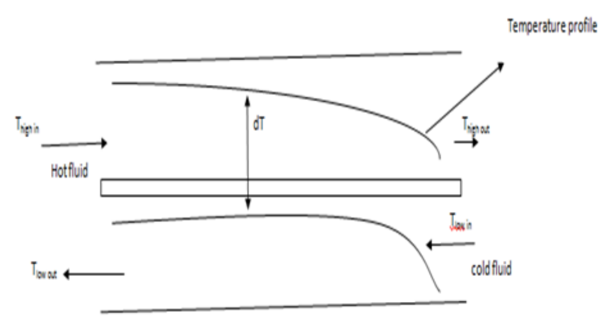


Figure: Temperature profile of hot and cold fluid when flown in opposite direction

Here T_{highin} is the inlet temperature of the hot fluid flowing in and $T_{highout}$ is the outlet temperature of hot fluid, similarly T_{lowin} and T_{lowout} are the temperatures of cold fluid of inlet and outlet flow.

If we observe clearly, the hot fluids and cold fluids are flowing in opposite direction and also the temperatures profile if we see clearly, for hot fluid it is decreasing and for cold fluid it is increasing indicating the transfer of heat energy from hot fluid to cold fluid through convection. The minimum temperature difference (dT_{min}) should be maintained between two fluids to ensure the transfer of heat energy

$$dT_{min} = T_{high} - T_{low}$$

this dT_{min} varies from substance to substance and it is different for different kind of applications but in general it varies from 4°c as the minimum value and maximum value cannot be defined.

After knowing how heat energy can be transferred from high temperature fluids to low temperature fluids, it is of great interest to know the amount of heat that can be transferred and this is given from the formula below

$$Q = M.Cp(Tout - Tin)$$

Here Q is the amount of heat transferred and M is the mass flow rate of transfer medium(air or liquid), Cp is the specific heat of the transfer medium, Tout is the temperature of the transfer medium flowing out of the system, Tin is the inlet temperature

If we know the inlet temperatures and outlet temperatures and if we want Q amount of heat transfer from the fuel cell system to vehicle interior, then the amount mass flow rate per unit time can easily determined provided whether the transfer medium is air or liquid by the formula

$$M = Q \div Cp(Tout - Tin)$$

Generally, for designing the heat transfer mechanism we take the transfer medium as air from the environment. as said earlier that heating is is only required in colder countries where the outside temperature is less than 10°c and air at this temperature consists with the moisture around 50%. However taking the liquid like water as transfer medium can be more benefit able from the point that it can recover more heat from the system but due to several reasons like maintenance of liquid container which are not desirable in mobility applications we assume transfer medium to be air from the environment

The broad schematic representation of the heat transfer mechanism taking air as transfer medium and the output is supplied to the vehicle interior directly for the space heating to keep it warm.

To design a transfer mechanism, firstly we should consider the starting mode where the fuel cell stack isn't in a position to provide the heat supply in that case a direct heating element is to be considered to ensure the proper supply of required heat to vehicle interior. Secondly , when the fuel cell stack is in operation mode and it can supply the heat energy. For this case in the first step air from environment (moisture content usually50%) is taken and the temperature is to be measured in order to determine pre heat temperature generally it would be in the range (5°c - 10°c). in the next step a pre heater is designed which sets pre heat conditions based on various considerations like outside air temperature, fuel cell operating temperatures and also the desired vehicle interior temperature (say in the region of 10°c - 15°c) . this is required to make sure that temperature to interior is properly maintained and in the next step the partially heated steam is supplied to fuel cell stack where it recovers the heat and now the stream temperature is once again measured to ensure the temperature is reaching required vehicle interior temperature . if the temperature of the fuel cell stack is not meeting the required value then it should be again feedback to the fuel cell stack to recover more heat. In the final step if the stream temperature and desired temperature matches, the hot air stream is directly pumped into the vehicle interior space to heat it. If this is not the case a direct heating element taking the input of both desired temperature and actual vehicle interior temperature is used to ensure the vehicle interior is heated up but this is not the desired case. to understand clearly , the inlet temperatures and outlet temperatures of various streams(1,2,3,4,5) are given in order to maintain a assumed vehicle interior temperature of 25°c.

By having the input temperature (Tin) and output or target temperature (Tout) we can calculate the mass flow by knowing the amount of heat to be transferred to the transfer medium.

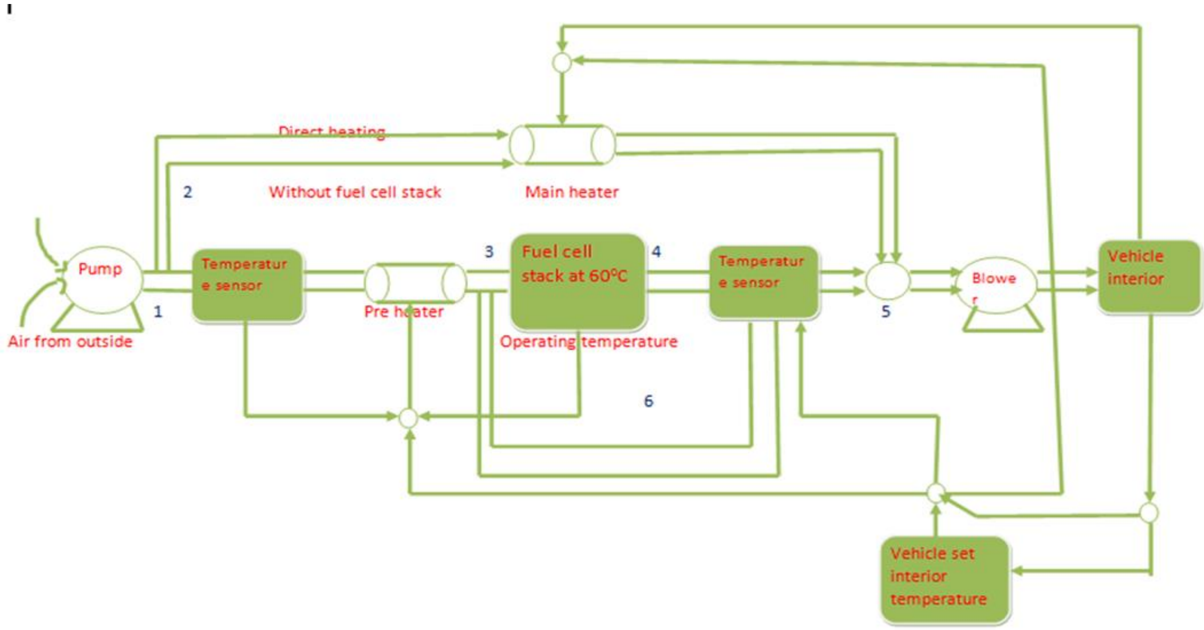


Figure: Heat transfer mechanism showing different components

Stream number	Stream description	Hot or cold	Supply temperature(T_{in})	Target temperature(T_{out})
1	Cold air from outside with moisture content more than30%	Cold	<10°C	-------
2	Stream after direct heating from main heater without use of fuel cell stack	Hot	<10°C	25°C
3	Stream after the pre heater	Medium hot	<10°C	15°C
4	Stream after fuel cell system	Hot	15°C	25°C
5	Stream either from FC system or from direct heating system	Hot	-----	25°C
6	Feedback stream from fuel cell system	Medium hot	<25°C	25°C

Table: Stream description inside the heat transfer mechanism with the supply temperatures and target temperatures

CONCLUSION

For any electric vehicle, the energy consumed by climatic control (heater or cooler) can be calculated by the formulae discussed in this paper. Similarly, the heat energy along with electrical energy can also be calculated for any fuel cell simply by knowing the reactants in the overall reaction, but in this paper, I had calculated it for PEMFC for understanding purpose. The heat thus liberated in the fuel cell is used to heat up the vehicle interior space, this heat recovery methods are also discussed along with the transfer mechanism. However, this mechanism isn't the fully operated and controlled yet and this needs to be simulated and implemented more in order to obtain the practical results. In this way the heat energy required for warming up the interior is taken from the fuel cell stack reducing the energy consumed thereby increasing the vehicle range along with keeping the vehicle interior heated up. The main drawback for this process is only during the starting of the vehicle where fuel cell cannot be used as heat source and at this stage interior needs to be heated by using the heating techniques like resistive heating. moreover, this method has hug benefit when implemented in a correct way making fuel cell electric vehicle a step forward towards the future mobility.

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