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# A double pipe heat exchanger design and optimization for cooling an alkaline fuel cell system

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**Abstract**

In the presented research heat transfer of a mobile electrolyte alkaline fuel cell (AFC) (where the electrolyte has a cooling role in the system) has been considered. Proper control volumes of system with specific qualifications have been chosen. Accordingly, heat and mass transfer in the control volumes have been assessed. Considerations of heat and mass transfer plus contributed models led to the use of a double tube heat exchanger as an energy sink. Design of this heat exchanger was dependent on heat transfer conditions and related equations. A composite system of alkaline fuel cells and peripheral equipment was used. Then the equations of all steps were integrated. Furthermore, the optimization codes were developed to propose the best operation point of the system, minimize total cost and determine the heat exchanger dimensions, flow rates and temperatures employing the 'GAMS' software. In the results, optimum electrolyte inlet and outlet temperature obtained were 73˚C and 40˚C, respectively; and the heat exchanger total area, minimizing the cost model, was rendered to 0.07 $m^2$. Finally, parametric analysis for variation of temperature, length and diameter of the heat exchanger, pressure drop, total cost and performance of planned combined system were studied. It was concluded that system cooling is very important because system efficiency decreases with rising temperatures. A promising fact of increasing overall efficiency of the system with regards to reducing electrolyte temperature demonstrated reducing electrolyte temperature in the range of 70 to 40˚C, resulted in a 2% increase in overall system efficiency.

## 1. Introduction

A fuel cell is an electrochemical system that converts chemical reaction energy to useful electrical energy and is made of an anode, cathode and electrolyte. The acronym, which describes the fuel cell type, refers to the type of the applied electrolyte or proton (or ion) conductor, with the exception of direct methanol fuel cells (DMFCs) where the type is identified by the contributed fuel. Development and application of fuel cell technology increase significantly through the analysis and improvement of heat transfer in

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the fuel cell stack and auxiliary components and by implementation of innovative heat transfer schemes that address those issues. Heat exchangers within fuel cells can be used as auxiliary devices to perform tasks such as water recycling, preheating, and cooling. An alkaline fuel cells or AFC is one of the low temperature systems and produces electricity through oxidation-reduction reactions between oxygen and hydrogen; electricity and heat are byproducts of this reaction [1]. In this system the electrolyte is an alkaline solution and how the electrolyte differs with use. These different modes can be as follows:
1. Alkaline fuel cells with mobile electrolyte,
2. Alkaline fuel cells with resident electrolyte, and
3. Alkaline fuel cells fuel solution [2].
A mobile electrolyte AFC system usually has peripheral equipment. Extensive studies were carried out on these systems; but specialty studies with a practical and an all purposes approach have not received enough attention. Although the central system produces the power, peripheral equipment must also be used and effect the whole system performance and total cost. In this research has been trying to survey the heat transfer of system and accessories in the optimal mode to increase efficiency and reduce costs. A circulated liquid electrolyte yields the product water and generated heat from the cell, and also allows for the possibility of removing carbonates from the electrolyte to prevent the decline of the cell performance. The circulation of the electrolyte within the alkaline cell is analogous to the circulation of coolant within PEM cells with the same complexity. The major difference between the two cells is that the alkaline cell must deal with a highly caustic electrolyte, requiring more care than the simple deionized water used in PEM technology. The fuel cells' heat recovery was the main aim of several research studies. Kordesch and Simader [3] pointed out that the circulation of the electrolyte can introduce parasitic current loops within the stack but they do not indicate any serious negative effects. Tomantschger et al. [4] added an explicit electrolyte heating loop in his designs, suggesting the use of the electrolyte to bring the cell up to operating temperature for the purpose of low temperature startup. Hwang et al. developed a heat recovery unit (HRU) in a proton exchange membrane (PEM) fuel cell cogeneration system that generates electricity and hot water efficiently. This cogeneration system can recover up to 50% of the fuel. The results showed that increasing external loads increases the electrical efficiency but slightly decreases the heat recovery efficiency. The maximum efficiency is 82% [7]. Many other subjects have attracted research attention such as mathematical modeling and optimization of heat exchangers applied to recover the heat from fuel cell [8-13]. Gao et al. proposed a numerical model of an exhaust heat recovery system for a high temperature polymer electrolyte membrane fuel cell (HTPEMFC) stack. The mentioned system is designed as thermoelectric generators (TEGs) sandwiched in the walls of a compact plate fin heat exchanger. The proposed model was based on a finite-element approach. On each discretized segment, fluid properties, heat transfer process and TEG performance are locally calculated to achieve more accurate model precision. Based on the sensitivity analysis it was found that exhaust gas parameters and the heat exchanger structure have a significant effect on the system power output and the pressure drop [8, 9]. In the presented research, heat transfer of a mobile electrolyte alkaline fuel cell (AFC) has been considered and a mathematical model was developed. Furthermore, the optimization codes have been developed to propose the best operation point of the system while minimizing total cost and determining the heat exchanger dimensions, flow rates and temperatures.

## 2. System configuration

A typical block diagram of a mobile electrolyte AFC system and the basic structure is shown in Fig.1.
Procedures in this type of systems are the flow loops of the electrolyte cycling between the anode and cathode plates, which cause the excess heat of the system to be ejected to a heat exchanger by the AFC. So, the electrolyte passes within a heat exchanger for cooling, before its re-entry into the system. A pump

is provided to the electrolyte flow cycle [2]. After determining assumptions, calculating electrical values and defining system qualification; heat transfer of the system can be studied.

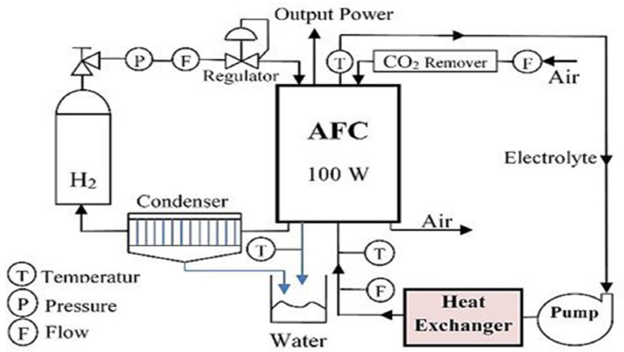


**Figure 1. Alkaline fuel cells with mobile electrolyte system and peripheral equipment [23].**

### 2.1. Heat Transfer

Heat transfer is important in fuel cell systems with cooling issues and for choosing materials. It should be noted that if the system is a mobile electrolyte mode cooling studies are in relation to electrolyte circulation. So, according to the rate of heat production in electrochemical reactions and selected materials, such as electrodes and walls (which transfer part of the produced heat to the environment), electrolyte circulation flow rate can be set somehow so that it rejects the waste heat from the system and keeps the system performance temperature constant at the ideal amount [15, 16]. According to the choice of the control volumes, heat transfer equations can apply to various parts or the whole system [17].

## 3. System Modeling

To begin calculations, a series of assumptions and initial conditions must be considered [18]. We assumed that the system produced 100W power and its performance was in atmospheric pressure. Potassium hydroxide has been chosen as the electrolyte and the type of system is a mobile electrolyte. It was also assumed that the produced water was in liquid form. Optimum values of voltage, current and power density, flow rates and cell area and stack design had been calculated already [24], and the results were used in this research to implement heat transfer studies. To evaluate heat transfer of the system the anode, cathode and system as a whole are considered as three distinct control volumes, and heat and mass transfer relationships are derived [19, 20]. The schema of control volumes is shown in Fig. 2. As seen, in the anode control volume the electrolyte, hydrogen and water flows stand; and is expressed in Eq. (1). The control volume of the cathode is shown in Fig. 2, and the electrolyte and air flow stand in this control volume. Eq. (2) is related to this section. The control volume of the overall system is shown in this figure, and the electrolyte, hydrogen, air and water flows stand in this control volume. Eq. (3) is related to the control volume of the overall system.

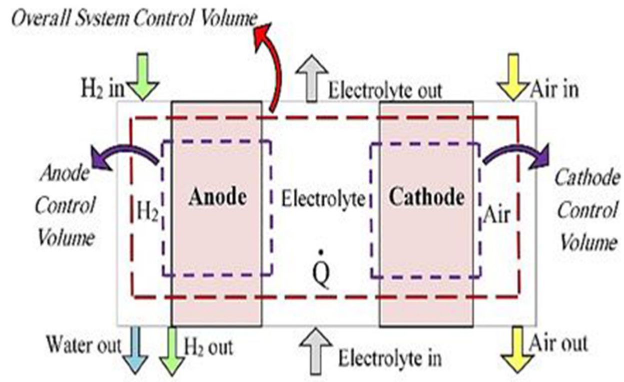


**Figure 2. Control volumes**

$$Q_{an}=\frac{\Delta T}{\left[\frac{1}{h_e A}\right]+\left[\frac{L}{K_{an} A}\right]+\frac{1}{\left[\left(\frac{1}{h_{H_2} A}\right)+\left(\frac{1}{h_w A}\right)\right]}+\left[\frac{L}{K_{wall} A}\right]+\left[\frac{1}{h_{amb} A}\right]}+Q_{gen,an} \quad (1)$$

$$Q_{ca}=\frac{\Delta T}{\left[\frac{1}{h_e A}\right]+\left[\frac{L}{K_{ca} A}\right]+\left[\frac{1}{h_{air} A}\right]+\left[\frac{L}{K_{wall} A}\right]+\left[\frac{1}{h_{amb} A}\right]}+Q_{gen,ca} \quad (2)$$

$$Q_t=I\left(\left[\frac{\Delta H}{nF}\right]+E_c\right)-m_{air}c_{air}(T_{ca,out}-T_{ca,in})-m_{H_2}c_{H_2}(T_{an,out}-T_{an,in})$$
$$-m_e c_e(T_{e,out}-T_{e,in})-m_w c_w(T_{an,out}-T_{prod})-h_{amb}A(T_{wall}-T_{amb}) \quad (3)$$

As noted, according to the system description, a heat exchanger is required for system cooling. For this purpose a double pipe heat exchanger is designed in [21] where electrolyte, as the warm fluid, flows in the inner tube; and water, as the cooling fluid, flows within the external tube as shown in Fig. 3. A proportional pump should be applied in order to having a circulating electrolyte stream.

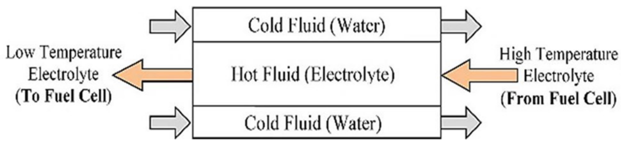


**Figure 3. Heat exchanger diagram.**

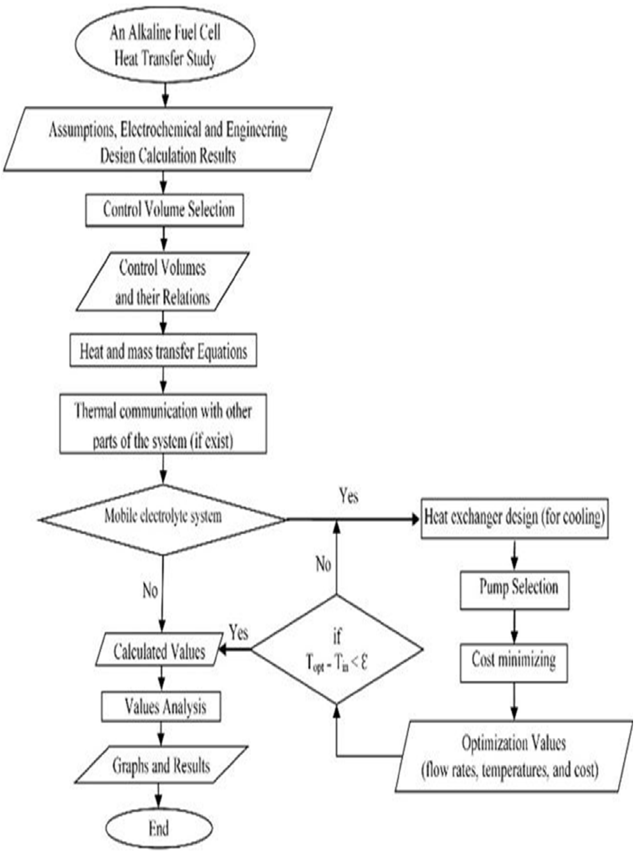


**Figure 4. Steps of study.**

### 3.1. Cost model

A mobile electrolyte alkaline fuel cell system requires peripheral equipment such as a hydrogen storage tank, a circulating pump to provide the electrolyte driving force, a heat exchanger as well as a series of additional process such as hydrogen production [22]. Therefore, in addition to the fuel cell there are other equipment costs that should be considered in the total cost. Finally, GAMS codes were developed utilizing the contributing heat transfer, heat exchanger design and cost model equations in order to minimizing total cost. In otherwords, the objective function was minimizing total cost with regards to the mentioned formula. Therefore, the optimal heat exchanger area, input and output flow rates and temperatures in the heat exchanger would be obtained based on the code of the algorithm in Fig. 4.

## 4. Results

It has been assumed that the inner tube diameter is 0.75 inch and outer tube diameter is 1.25 inch. Also, the inlet water temperature has been considered 15˚C. Obtained optimum heat exchanger area and dimensions are listed Table 1:

**Table 1. Optimum heat exchanger area and flow rates.**

| | |
|---|---|
| Mass flow rate of electrolyte | $1.6\times10^{-4}$ (kg/s) |
| Cold fluid mass flow rate (Water) | $2.827\times10^{-4}$ (kg/s) |
| Area of heat exchanger | 0.07 ($m^2$) |
| Length of heat exchanger | 0.44 (m) |
| Pressure drop | $5.2\times10^{-4}$ (Pa) |

Temperature of fluids and total heat transfer in optimal mode are listed in Table 2.

**Table 2.Optimum temperatures and heat transfer rate.**

| | |
|---|---|
| Electrolyte inlet to heat exchanger and outlet of cell temperature | 73 (˚C) |
| Electrolyte outlet of heat exchanger and inlet to cell temperature | 40 (˚C) |
| Cold fluid outlet temperature (Water) | 25 (˚C) |
| Total heat transfer rate | 121.7(W) |

## 4.1 Sensitivity analysis

In order to evaluate the results quantification, a sensitivity analysis was developed on the input parameters of the models. All investigated parameters are listed in Table 3. The effect of parameter variations on the obtained length of heat exchanger was investigated in the given interval and the results of the sensitivity analysis are illustrated in the spider diagram shown in Fig. 5. It can be concluded that variation in inlet water temperature has the least impact and the inlet electrolyte temperature has the most effect on the length of the heat exchanger. By increasing the inlet water temperature, the length of heat exchanger increased in a semi linear manner. In the case of inlet electrolyte temperature variations, the variations were linear at values higher than the reference value, but if the values were lower the variations became non-liner. As can be seen in Fig. 5, a 10% decrease in relation to the reference value of the inlet electrolyte temperature leads to an increase the length of heat exchanger from approximately 0.45 to 0.8. It can also be seen that the inlet electrolyte temperature has more sensitivity related to the heat exchanger's length as compared with the outlet water temperature.

**Table 3. Temperature profiles variations and their investigated interval included in the sensitivity analysis.**

| Patameters | Symbol | Referece value | Interval | Length of heat exchanger (m) |
|---|---|---|---|---|
| Intel water tempreture (Heat exchanger) | $T_{w,in}$ | 15 | [6...24] | [0.2544...0.7186] |
| Outlet water tempreture (Heat exchanter) | $T_{w,out}$ | 32 | [16...48] | [0.7186...0.1947] |
| Inlet electrolyte tempreture (Toward heat exchanger) | $T_{e,in}$ | 80 | [60...100] | [1.099...0.2252] |
| Outlet electrolyte tempreture (Outward heat exchanger) | $T_{e,out}$ | 35 | [20...50] | [0.1399...1.099] |

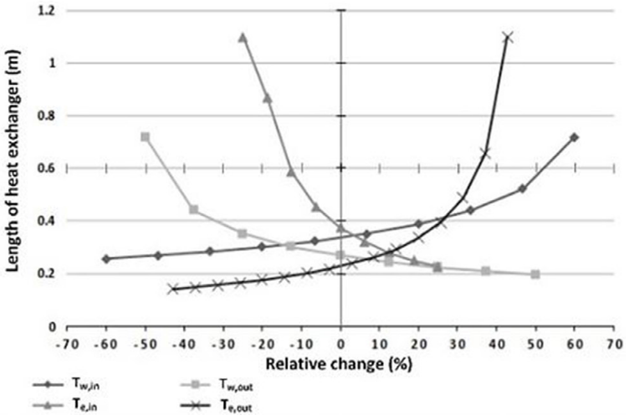


**Figure 5. Effect of input and output temperatures on length of heat exchanger.**

Following a similar approach, sensitivity analysis was carried out on the efficiency and cost of the system. In Table 4 all investigated parameters are listed in Table 4. Effect of parameters on the efficiency and cost of the system in the given period were studied. The contribution of the sensitivity analysis to efficiency are illustrated in two scenarios (as defined $T_{e,out}$ = 70, 90˚C). The results are illustrated in spider diagrams shown in Figs. 6 and 7 for the purpose of review in efficiency and cost, respectively.

**Table 4. Efficiency and cost variations and their investigated interval included in the sensitivity analysis**

| Patameters | Symbol | Referece value | Interval | Effiiciency (%) | Cost ($) |
|---|---|---|---|---|---|
| Intel electrolyte tempreture to heat exchanger ($T_{e,out}$=70) | $T_{e,in}$ | 37.5 | [20...55] | [36.73...39.19] | [2700.9...2697.2] |
| Intel electrolyte tempreture to heat exchanger ($T_{e,out}$=90) | $T_{e,in}$ | 55 | [30...80] | [38.97...41.32] | [1657.7...3454.4] |
| Area of heat exchanger ($T_{e,out}$=70) | A | 0.077195 | [0.068...0.1103] | [37.122...39.2] | [2700.9...2697.2] |
| Area of heat exchanger ($T_{e,out}$=90) | A | 0.065543 | [0.1863...0.022] | [39.25...41.4] | [1657.7...3454.4] |
| Mass flow rate of electrolyte ($T_{e,out}$=70) | m | 0.1118 | [0.171...0.0513] | [36.8...39.2] | [2700.9...2697.2] |
| Mass flow rate of electrolyte ($T_{e,out}$=90) | m | 0.1367 | [0.0513...0.222] | [38.97...41.32] | [1657.7...3454.4] |

According to Fig. 6, it seems that a rise in outlet electrolyte temperature between 70 to 90˚C leads to increased efficiency. In scenario $T_{e,out}$ = 70˚C, an increase in input electrolyte temperature, led to a linear increase in efficiency. Contrarily, increasing the electrolyte flow rate, led to a linear decrease in efficiency. The relationship between the heat exchanger area and the efficiency included two sections. First, reducing the area by 8%, compared to the reference value, increased efficiency from 36.7 to 37.5. So, increasing the area caused the system efficiency to increase in an approximately linear manner. Therefore, it can be said that is optimal for the area relative to system efficiency in scenario $T_{e,out}$ = 70˚C.

For $T_{e,out}$ = 90˚C, increasing the inlet temperature and the electrolyte flow led to an increase in system efficiency. In the case of heat exchanger area, an increase in the variations relative to the reference value caused a decrease in the system efficiency. According to the results indicated in Fig. 7 and considering the sensitivity analysis of the system efficiency, we can see that higher efficiency caused lower costs and vice-versa. In other words, in the $T_{e,out}$ = 90˚C scenario, when the efficiency is higher the relative reduction of the surface area related to the reference value from -50% to -70% caused an increase in the system cost from \$2700 to \$3290. Also, the input electrolyte temperature increased from 5% to 45% and the electrolyte flow rate increased from 7% to 62% which in turn caused an increase in the system cost from \$2600 to \$3450. In the $T_{e,out}$ = 70˚C scenario, variations in the input electrolyte temperature and the electrolyte flow rate had a negligible effect on the total system cost. Similar to Fig. 2, the relationship between the heat exchanger area and the cost can be divided into two sections. First, when the area related to the reference value decreased 6% the cost was reduced from \$2700 to \$2650, but increasing the area rarely produced a constant system cost.

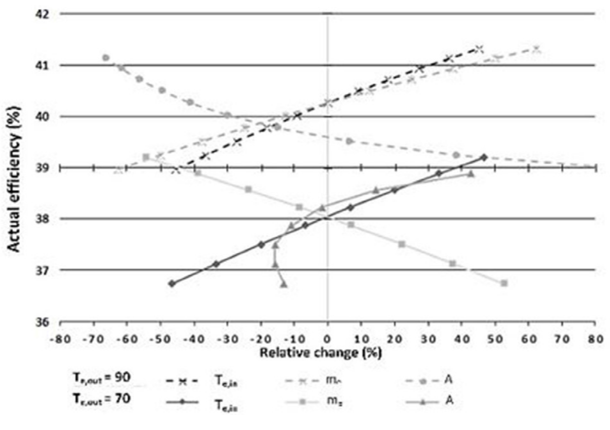


**Figure 6. The relative variables versus actual efficiency.**

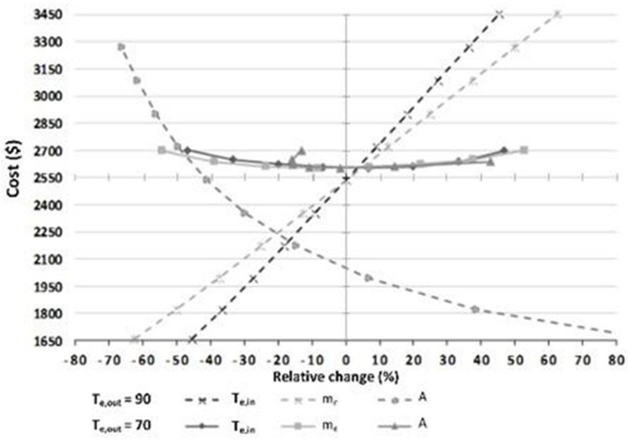


**Figure 7. The relative variables versus cost.**

The performance of the cell is under the influence of different factors such as temperature. In order to study the effect of temperature on cell performance and entire system (cell and peripheral equipment), the graphs of system efficiencies with regards to temperature are depicted in Fig. 8. Based on Eq. (4) and Eq. (5) it can be concluded that the gradient is less than the ideal performance of the cell because of a reduction in the sensitivity of the total system toward temperature due to the existing cooling section.,

$$\text{Ideal efficiency} = \frac{\Delta G}{\Delta H}\times 100\% = \frac{ROCV.I\,t}{\Delta H} \quad (4)$$

$$\text{Real efficiency} = \frac{E_c.I\,t}{\Delta H}\times 100\% \quad (5)$$

Based on Eqs. (6) to (8), Fig. 9 shows that increasing the length of the heat exchanger pipes in addition to increasing total cost, intensified the pressure drop and in this way effected the pumping system (capital cost and energy cost) and thereupon growth of total cost.

$$A = \frac{\dot{Q}}{U_0.\Delta T_{LMTD}} \quad (6)$$

$$C_{Hex} = C_{HE}.A_{HE}\ ;\ C_{HE} = 350 \quad (7)$$

$$\Delta P = \frac{2f\rho u^2 L_{HE}}{d_i} \quad (8)$$

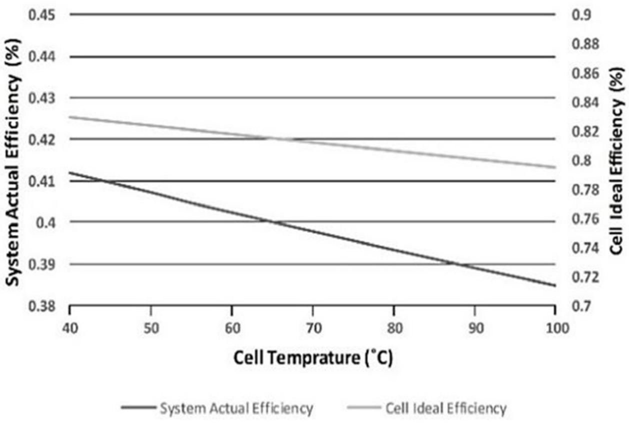


**Figure 8. System efficiency versus performance temperature.**

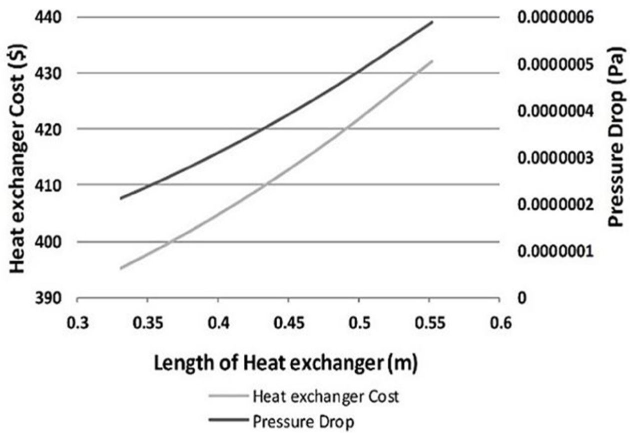


**Figure 9. Cost and pressure drop changes by the length of heat exchanger.**

## 5. Conclusions

In the presented research a mobile electrolyte alkaline fuel cell and its peripheral equipment have been discussed with a heat transfer and cooling approach. An algorithm has been offered to achieve a design model. The presented model has been optimized using GAMS codes to find optimum values for the cost model, heat transfer equations and designed heat exchanger. The results obtained showed that cooling of the system was very important and played a main role in the overall efficiency of the system as when temperatures rose the efficiency fell. This was demonstrated when a reduction of electrolyte temperature from 70 to 40˚C resulted in an overall 2% increase in system efficiency. The quantification of results was based on formulas 4 and 5 and also the trend calculation of Figure 8. Finally, it was concluded that heat transfer and cooling of system, electrolyte inlet and outlet temperatures, heat exchanger length and diameter are some of the parameters that effect cell performance, pressure drop, ideal heat exchanger and naturally total cost.

**Nomenclature**

| | |
|---|---|
| $A$ | Heat exchanger area ($m^2$) |
| $c$ | Specific heat capacity (j $kg^{-1}$ $˚K^{-1}$) |
| $C_{Hex}$ | Total cost of heat exchanger ($) |
| $C_{HE}$ | Cost per unit area ($ $m^{-2}$) |
| $d_i$ | Internal pipe diameter (m) |
| $E_c$ | Cell voltage (Volt) |
| $f$ | Friction coefficient |
| $F$ | Faraday constant (coulomb $mol^{-1}$) |
| $G$ | Gibbs free energy (j) |
| $h$ | Convectional heat transfer coefficient (W $m^{-2}$ $˚K^{-1}$) |
| $H$ | Enthalpy (j) |
| $I$ | Current (A) |
| $K$ | Thermal conductivity ($Wm^{-1}$ $˚K^{-1}$) |
| $L$ | Thickness (m) |
| $L_{HE}$ | Length of heat exchanger (m) |
| $LMTD$ | Logarithmic Mean Temperature Difference |
| $m^{\cdot}$ | Mass flow rate (kg $s^{-1}$) |
| $n$ | Number of electrons in electrochemical Reaction |
| $P$ | Pressure (Pa) |
| $Q^{\cdot}$ | Heat transfer rate (j $s^{-1}$) |
| $ROCV$ | Reversible Open Circuit Voltage |
| $t$ | Time (s) |
| $T$ | Temperature (˚C) |
| $u$ | Velocity (m $s^{-1}$) |
| $U_0$ | Total heat transfer coefficient (W $m^{-2}$ ˚K) |

**Subscripts**

| | |
|---|---|
| *air* | Air |
| *amb* | Ambient |
| *an* | Anode |
| *ca* | Cathode |
| *cell* | Cell |
| *e* | Electrolyte |
| *gen* | Generation |
| $H_2$ | Hydrogen |
| *prod* | Production |
| *t* | Total |
| *w* | Water |
| *wall* | Wall |

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