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# 3D Modeling & Numerical Simulation of Heat transfer of Back-pack Thermoelectric Cooling Helmet validated By Experimentation at Hot Environment

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**ABSTRACT**

**This paper reports the performance prediction and analysis of a back-pack thermoelectric cooling helmet through Computational Fluid Dynamics (CFD). This cooling system (helmet) works on the Principle of thermoelectric cooling based on Peltier effect. The system is divided into two parts namely cold side and hot side of thermoelectric system. The cold side components are blower, divergent duct, cold plate and convergent duct whereas the hot side components are Aluminium block, heat pipe, fins and fan. The array of thermoelectric modules are sandwiched between these Cold Side and hot side components. The cold side analysis is performed through CFD and hot side calculation is based on empirical formulas. A comparative study of performance of these designs are carried out for different types of blower and hot side fan combinations for three different thermoelectric modules which predicted that it is possible to get enough cooling not only at the top of head but also some portion of face by spraying cold air through the back-pack thermoelectric cooling system. This also directly affect the physiological performance of human.**

***Key words: Peltier Effect, Thermoelectric Cooling Helmet, Computational fluid dynamics, heat transfer, heat pipe, volume flow rate, Pressure drop***

## 1. INTRODUCTION

R&D Division of MECON LTD., Ranchi has done extensive work on thermoelectrics since last 30 years [1-5]. The present work is in continuation to the previous work done on thermoelectric at hot environment.

Working temperatures in the premises near hot furnaces are usually higher; hence working under this high temperature condition is uncomfortable. A safety helmet is used to cool the high temperature air to comfortable level and supplies it to head & face of the Industrial workers. The cooling system works on the principle of thermoelectric cooling based on Peltier Effect. This effect is observed when direct current is allowed to flow across the junction of two dissimilar conductors. The junction region is found to either absorb or release heat depending on the direction of the current. The thermoelectric cooling system has been developed by using a number of thermoelectric modules suitably connected to cold side plate and hot side heat exchanger. By passing air through the cold side plate, the air is cooled and circulated through head and some portion of the face, which gives the full comfort to the worker, working at elevated temperature zone. Designs of cold plate were done with analysis parameters based on different blowers, fans and TE modules. Figure 1 shows the typical concept of Back-pack cooling helmet.

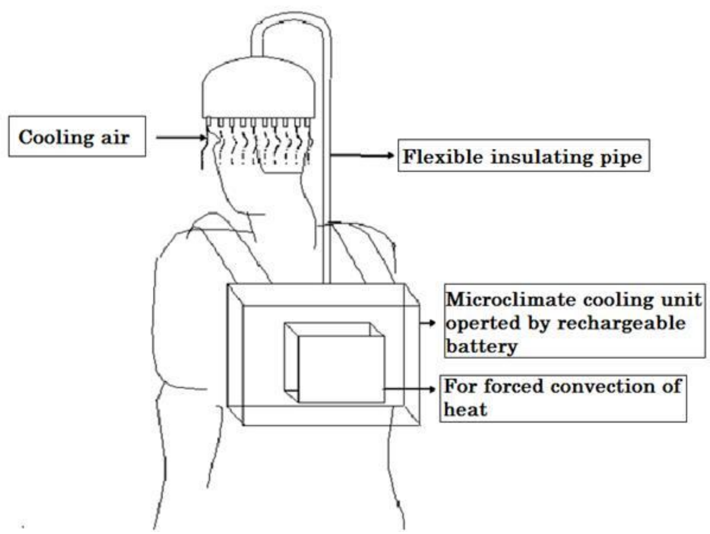


**Figure 1: Typical concept of Back-pack head & face cooling helmet for human working at hot environment.**

System with hybrid heat sink (convective and heat pipe both) unit with TE Modules, small fans, blower and rechargeable battery to be carried as back pack. Electric switch fixed with waist belt. Cold air, by blower through flexible pipe, to be carried to head. The flexible pipe will enter through holes in the helmet and through the small holes in the pipe; the cold air will be distributed to cool the head and some portion of face, which gives the comfort to the worker working at elevated temperature. The charger is also designed to recharge the discharge battery. Additional head load is almost nil.

From our literature and patent search [6-14], it is concluded that some work was conducted at different parts of world on cooling/heating helmets, but the technique and approach was quite different compared to our present system. It is also observed that our present system is capable to operate at high ambient temperature i.e. more than 50°C with an Indian Industrial hazardous environment.

## 2. TECHNICAL APPROACH

The typical combination and components of Back-pack thermoelectric cooling helmet with technical designs and approach are explained below:

### 2.1 Heat Sink Assembly

Figure 2 shows the complete heat sink assembly. It has components like inlet duct (divergent), cold plate, outlet duct (convergent), TE modules, Aluminium block, heat pipe, fins, and fan.

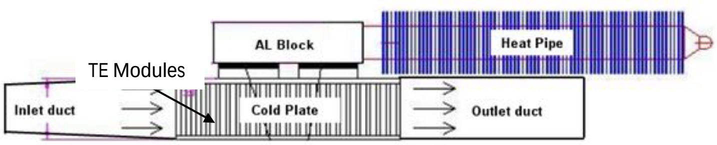


**Figure 2: Typical Heat Sink Assembly**

### 2.2 Blower

Hot ambient air is forced to flow through cold plate by blower. Proposed blowers are DC Radial, Type 1 Series, Capacity 17 CFM and Type-2 Series, Capacity 35 CFM. Even though the maximum rated capacity for each blower is high i.e. 17 CFM & 35 CFM, when integrated with cold plate designs, which generate relatively low volume flow rates i.e. between 1.5 & 5.0 CFM. This is because of large pressure drop that cold plates cause to flow. However, the blower options are appropriate as they are designed to generate enough pressure drops to make flow through the cold plate. The final selection is based on minimum flow rate requirements

### 2.3. Cold Plate

Divergent and convergent ducts guide the flow through cold plate. Cold plate has several baffles which retards the flow and helps in heat transfer. Such cold plate designed as shown in figure 2 are considered for analysis.

### 2.4. Thermoelectric modules (TEM)

Three different types of thermoelectric modules, named TEM-1, TEM-2 and TEM-3, are considered in this analysis. TEM-1 is operated by 12 V DC with 4.14 Amps. of Current, which extract 30 Watts of heat (Qc) from head. TEM-2 is operated by 12 V DC with 6.16 Amps. of current, which extract 34 Watts of heat (Qc) from head. TEM-3 is operated by 12 V DC with 5.48 Amps. of current, which extract 30 Watts of heat (Qc) from head. TE-module (TEM) takes heat from hot air through the cold side and dissipates it through hot side. Table 1 shows three different types of thermoelectric modules considered in this analysis.

**Table 1 Initial Design - TE Modules**

| TEC | Voltage (V) | Current (A) | Qc (W) |
|---|---|---|---|
| TEM1 | 12 | 4.14 | 30 |
| TEM2 | 12 | 6.16 | 34 |
| TEM3 | 12 | 5.48 | 30 |

Two such TE modules were used in parallel on one side of cold plate. Keeping all components same, choosing TEM-3 module brings down the exit temperature by 2.3°C compared to what is obtained by using TEM-1. Similarly, choosing TEM-2 module brings down the exit temperature by 4.2°C compared to what is obtained by using TEM-1.

### 2.5. Hot Side Components

The heat loss rate through the hot side can be written as:

$$Q = h_{eff} (T_{TEC\_HotSide} - T_{amb})$$

The effectiveness of hot side design can be gauged from the value of effective heat transfer coefficient, $h_{eff}$. Higher the value of $h_{eff}$, more would be the amount of heat that can be dissipated away [15-16]. Typical value of $h_{eff}$ is 25.8 W/°C. Therefore, a 3 degree difference between Thermoelectric System (53°C) & ambient temperature (50°C) would dissipate 75W of heat.

As a general guideline, analysis of data reveals that 10% increase in $h_{eff}$ reduces the cold plate exit temperature by 0.13°C.

### 2.6. Heat Pipe

Heat dissipated from hot side of TE modules is transferred to heat pipe through Aluminium block. It is assumed that there is no heat loss (convection and conduction) from Aluminium block and hot side TEM temperature is taken as input to heat pipe.

Increasing the length of heat pipe & keeping the number of fins same would not have any impact on heat dissipation quality of hot side assembly [17]. However, introduction of more number of fins on the heat pipe (keeping the gap between fins as 2 mm), improvement in heat dissipation is possible. Analysis of numerical data reveals that for obtaining a reduction of 0.5°C in cold side exit temperature, the heat pipe length should be increased from 150 mm to 200mm [18].

### 2.7. Hot Side Fins

A number of equally spaced of fins are used to finally dissipated heat to atmosphere. Heat transfer rate depends on thickness of fins and spacing between them. There are 76 fins with dimensions 140 mm x 30 mm with 2 mm gap between them. The heat transfer coefficient is directly proportional to the extended area generated by the fins [19]. Hence, by increasing number of fins, a proportional increase in heat transfer coefficient can be obtained. However, it is not possible to increase the number of fins on the available heat pipe because (i) it is difficult to manufacture fin assembly with gap less than 2 mm & (ii) lesser gap would lead to deterioration in $h_{eff}$ because width of thermal boundary layers on fin would increase & may overlap [20].

### 2.8. Hot Side Fan

It is used to facilitate forced convection heat transfer from hot side fins. Volume flow rate for fan is being investigated for desired design performance.

The study has investigated usage of four axial fans i.e. 4412L, 4412M, 4412N & 4412H with corresponding volume flow rates of 88.30, 108.89, 120.66 & 147.15 CFM, respectively. On analysis, these four fans give value of $h_{eff}$ as 22.6W/°C, 25.1W/°C, 26.4W/°C & 29.2W/°C respectively.

For every 20CFM increase in hot side fan volume flow rate, we find a marginal drop of 0.11°C in cold plate exit temperature. However, reducing CFM values can have drastic deterioration in $h_{eff}$ because width of thermal boundary layers on fin would increase & may overlap.

## 3. METHODOLOGY-CFD ANALYSIS

Flow through divergent duct, cold plate, and convergent duct is analyzed using CFD tools. Domain as shown in Figure 3 is divided into several hexahedral cells and with proper boundary conditions, each property is computed at the centers of cells by solving standard fluid flow equations at each time step. Outcome of CFD simulation is in terms of flow and temperature profiles.

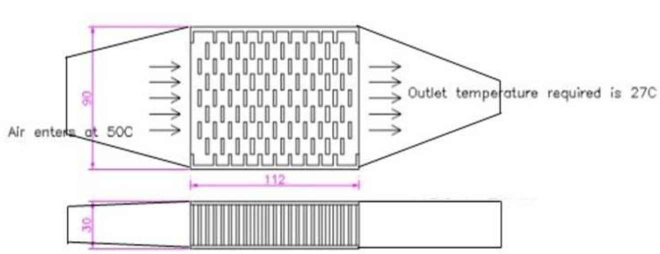


**Figure 3: Domain for CFD Analysis**

### 3.1. System Level Analysis

Outcome of initial CFD analysis is taken as base for predicting performance of the system. Volume flow rate value for blower is chosen first to match cold plate pressure drop from given blower characteristics. For hot side fan, similar procedure is performed. Then corresponding cold plate outlet temperature is calculated which matches TE module input power requirements. From CFD analysis, mean baffle temperature is predicted and corresponding heat transfer coefficient value is calculated. This calculated heat transfer coefficient is used to predict new coefficient for different values of blower and hot side fan volume flow rate. Finally values of temperature at the hot side of TE module and total heat dissipated from hot side are then calculated. [21]

The details of the system level analysis are given below:

Heat transfer rate,

$$\dot{Q}_{cTEC} = \dot{m}\, c_p (T_{amb} - T_{out})$$

where,

$\dot{m}$ is mass flow rate

$c_p$ is specific heat capacity of air

$T_{amb}$ is ambient air temperature in °C

$T_{out}$ is cold plate exit temperature in °C

**Mass flow rate**

$$\dot{m} = \dot{Q}_{cTEC} / (c_p\ (T_{amb} - T_{out}))$$

also,

$$\dot{m} = \rho A V$$

where,

ρ is density of air

A is cross-sectional area of divergent duct inlet

**Velocity at inlet of cold plate,**

$$V = \dot{m} / (\rho A)$$

**Heat flux required on the cold side of each TEM as boundary condition for CFD,**

$$\dot{q}_{TEC} = \dot{Q}_{cTEC} / A_{TEC}$$

where,

$A_{TEC}$ is Surface cross section area of TEC module

**Heat transfer rate to TE modules,**

$$\dot{Q}_{cTEC} = \dddot{V}\, \rho c_p (T_{amb} - T_{out})$$

$\dddot{V}$ = Volume flow rate of air in $m^3/s$

(**1 CFM** = ft * ft * ft / minute = 0.3048m*0.3048m*0.3048m / 60 sec = **0.000472 $m^3/s$**)

**Convective heat transfer coefficient for cold plate,**

$$h_{coldplate} = \dot{Q}_{cTEC}\ / (A_{fluid}\ (T_{amb} - T_{out}))$$

where,

$A_{fluid}$ is baffle surface area in contact with air

**New heat transfer coefficient,**

$$h_{coldplate\text{-}new} = h_{coldplate}\ (\dddot{V}_{new} / \dddot{V})^{0.57}$$

where,

$\dot{V}$ = Volume flow rate of blower for CFD calculation

$\dot{V}_{new}$ = Volume flow rate of new blower

### 3.2. Design Description-Drawings and dimensions

Figure 4 shows dimensions of Initial cold plate. Following are the details the dimensions of Cold plate.

Cold plate dimensions: 112 mm x 90 mm x 27 mm, Inflow boundary dimensions: 58 mm x 27 mm, Outflow boundary dimensions: 20 mm x 30 mm, Divergent duct length: 100 mm, and Convergent duct length: 110 mm

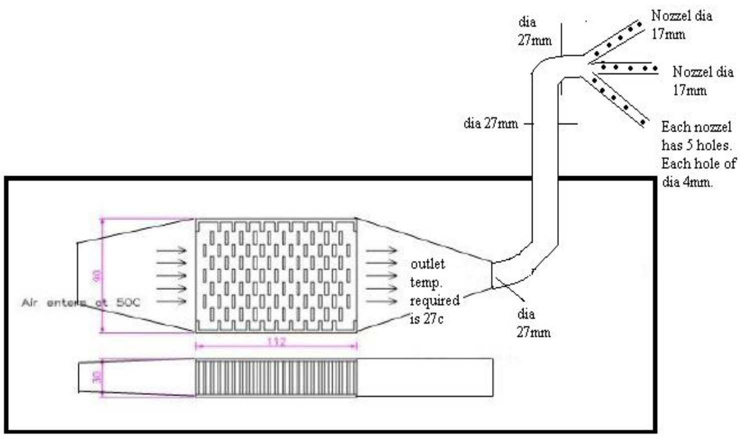


**Figure 4: Initial Design – Dimensions.**

### 3.3. CFD Simulation with Domain Creation and Mesh Generation

First, extents of the domain are defined and a 3D structured multi-block topology is created. Several planes are cut at boundaries of cold plate baffles. Thickness of cold plate and each baffle are assigned label “solid”. Rest of the domain is “fluid”. Generated mesh is converted into hexahedral unstructured mesh which is given as input to the CFD solver. Figure 5 shows multi-block topology used for this simulation.

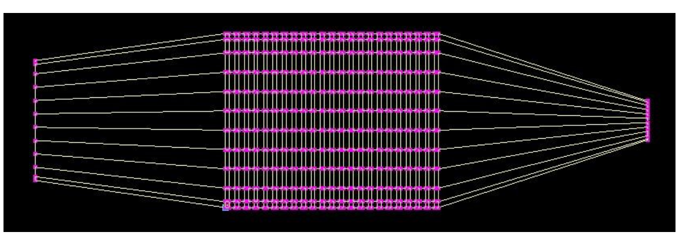

**Figure 5: Initial Design - Multi-block Topology**

The figures 6 and 7 show corresponding “fluid” and “solid” zones in generated volume mesh respectively.

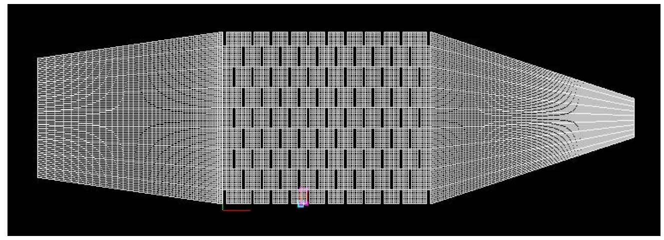

**Figure 6: Initial Design - Volume Mesh for Fluid Zone**

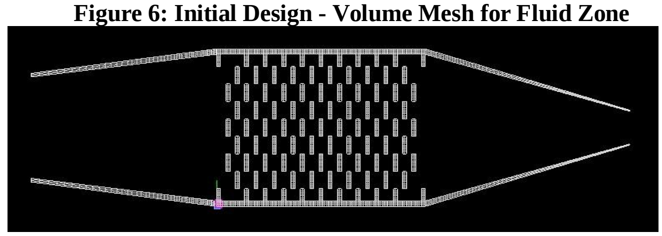

**Figure 7: Initial Design - Volume Mesh for Solid Zone**

***Boundary Conditions***

Figure 8 shows boundary conditions applied to the CFD domain in order to carry out the simulations.

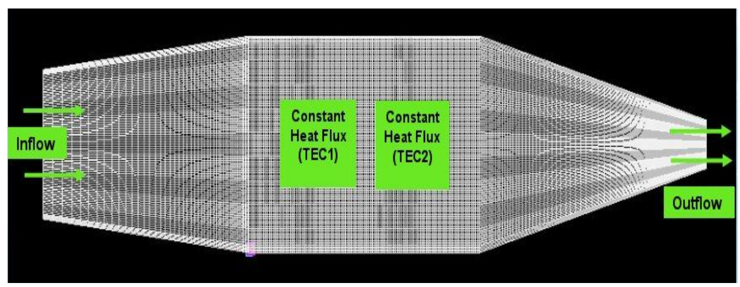


**Figure 8: Initial Design - Boundary Conditions**

The following data shows type of boundary conditions and values specified:

<u>Inflow Boundary Condition</u>

V = 0.67587 m/s

T = 50 °C

<u>Outflow Boundary Condition</u>

T = 27 °C

<u>Outflow Boundary Condition</u>

For each TEC module, Heat flux value is calculated as,

$q = 15\ W / (0.03 \times 0.03)\ m^2 = 16666.67\ W/m^2$

All other boundaries are considered as adiabatic walls.

**Flow Property Variation**

Figures 9 and Figure 10 show Pressure and Velocity-X variations computed through CFD for the domain.

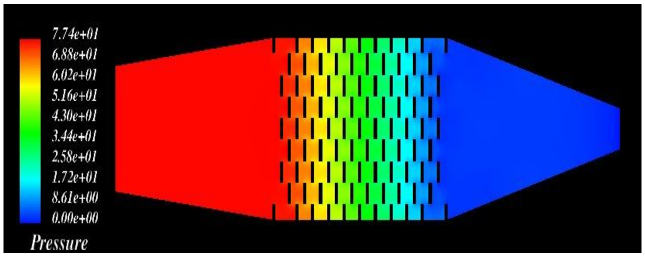


**Figure 9: Boundary Conditions - Pressure Contours**

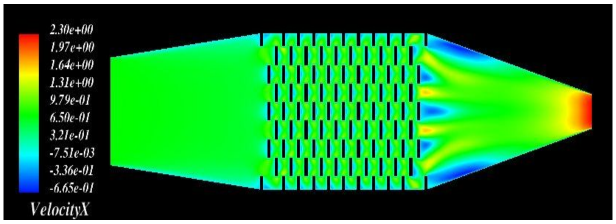


**Figure 10 Initial Design - Velocity-X Contours**

**Temperature Distribution**

Figure 11 shows temperature profile (in °K) on the section taken at the middle of domain when viewed from front. Figure 12 shows the temperature contours when section is taken along normal plane when viewed from top.

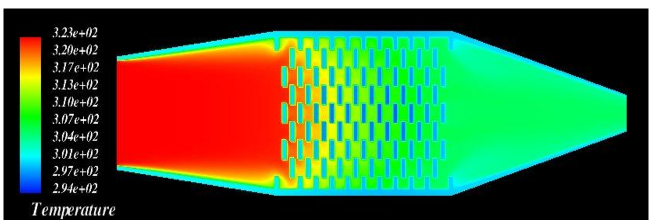


**Figure 11: Initial Design - Temperature Contours at mid section plane (Front View)**

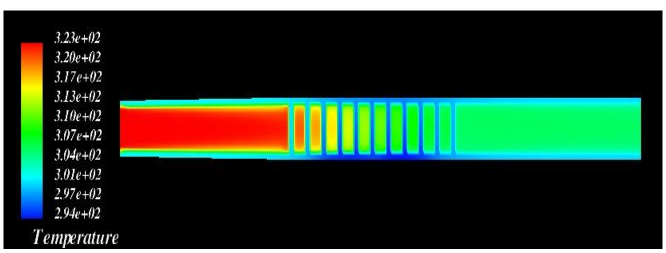


**Figure 12: Initial Design - Temperature Contours on Normal section plane (Top View)**

## 4. CFD SIMULATION OUTPUTS

With given flow and thermal boundary conditions, the computed pressure drop across the cold plate is 77.5 Pa for which pressure coefficient is calculated. The temperature values at cold side of TE modules are 22.886 °C and 22.284 °C for TEM-1 and TEM-2 respectively. Heat transfer coefficient obtained is 55.58 W/$m^2$ and mean cold plate baffle temperature is 26.601 °C.

### 4.1. Performance Estimation

For requirement of given TEM capacity and given cold plate inlet and outlet temperature values, blower volume flow rate is 2.24265 CFM and divergent inlet velocity is 0.6759 m/s. TEM cold side and hot side temperature values are 24.828 °C and 56 °C respectively. The input power requirement to TEM modules is 49.76 W. Corresponding total heat dissipated from hot side is 79.76 W.

This design is corresponding to theoretically calculated blower CFM value. If a blower with this CFM value is available, it can be directly used. Otherwise a corresponding point on blower characteristics (for available given blower) is chosen.

### 4.2. Design Analysis - Component Selected

Tables 2 and 3 show blower and hot side fan types used.

**Table 2 Initial Design - Blower Types**

| BLOWER | TYPE1 | TYPE2 |
|---|---|---|
| B1 | Type 1/12ML | Type 2/12 |
| B2 | Type 1/12 | Type 2/12H |

**Table 3: Initial Design – Hot Side Fan Types.**

| HOT SIDE FAN | TYPE DC Axial Fans | VOLUME FLOW RATE (CFM) |
|---|---|---|
| F1 | 4412L | 88.30 |
| F2 | 4412M | 108.89 |
| F3 | 4412N | 120.66 |
| F4 | 4412H | 147.15 |

**Calculations for Blower Type 1 Series**
**Blower Characteristics**

Table 4 shows values for the points chosen on blower characteristics curve

**Table 4 Initial Design - Blower Characteristics**

| BLOWER | VOLUME FLOW RATE (CFM) | PRESSURE DROP (Pa) |
|---|---|---|
| Type 1/12 ML (B1) | 2.4135 | 89.76 |
| Type 1/12 (B2) | 3.0312 | 141.58 |

### Cold and Hot Side Calculations for different Thermoelectric Modules

The tables 5, 6 and 7 show cold and hot side analysis for TEM1, TEM2 and TEM3 respectively with Type 1 Series blower.

**Table 5 Initial Design - Calculations for one Blower (TEM1)**

| Blower-Fan Combination | Blower Air Flow (CFM) | Cold Plate Pressure Drop (Pa) | Fan Air Flow (CFM) | Cold Plate Exit Temp (°C) | TEC Temp (Cold Side) (°C) | TEC Temp (Hot Side) (°C) | Heat Diss. From Hot Side (W) |
|---|---|---|---|---|---|---|---|
| B1-F1 | 2.4135 | 89.76 | 88.30 | 28.21670 | 25.67025 | 53.55752 | 80.25513 |
| B1-F2 | 2.4135 | 89.76 | 108.89 | 28.10700 | 25.54773 | 53.21020 | 80.42129 |
| B1-F3 | 2.4135 | 89.76 | 120.66 | 28.05700 | 25.49188 | 53.05190 | 80.48152 |
| B1-F4 | 2.4135 | 89.76 | 147.15 | 27.96700 | 25.39136 | 52.76695 | 80.57970 |
| | | | | | | | |
| B2-F1 | 3.0312 | 141.58 | 88.30 | 31.71000 | 28.17825 | 53.63156 | 81.92530 |
| B2-F2 | 3.0312 | 141.58 | 108.89 | 31.61600 | 28.06610 | 53.27748 | 82.10678 |
| B2-F3 | 3.0312 | 141.58 | 120.66 | 31.57300 | 28.01479 | 53.11551 | 82.15909 |
| B2-F4 | 3.0312 | 141.58 | 147.15 | 31.49600 | 27.92292 | 52.82547 | 82.28402 |

**Table 6 Initial Design - Calculations for one Blower (TEM2)**

| Blower-Fan Combination | Blower Air Flow (CFM) | Cold Plate Pressure Drop (Pa) | Fan Air Flow (CFM) | Cold Plate Exit Temp (°C) | TEC Temp (Cold Side) (°C) | TEC Temp (Hot Side) (°C) | Heat Diss. From Hot Side (W) |
|---|---|---|---|---|---|---|---|
| B1-F1 | 2.4135 | 89.76 | 88.30 | 23.06500 | 19.91632 | 54.95114 | 111.69409 |
| B1-F2 | 2.4135 | 89.76 | 108.89 | 22.87100 | 19.69964 | 54.47026 | 111.98801 |
| B1-F3 | 2.4135 | 89.76 | 120.66 | 22.78300 | 19.60136 | 54.25213 | 112.13285 |
| B1-F4 | 2.4135 | 89.76 | 147.15 | 22.62400 | 19.42377 | 53.85801 | 112.35382 |
| | | | | | | | |
| B2-F1 | 3.0312 | 141.58 | 88.30 | 27.04600 | 22.61364 | 55.06945 | 114.36309 |
| B2-F2 | 3.0312 | 141.58 | 108.89 | 26.87700 | 22.41201 | 54.57876 | 114.70606 |
| B2-F3 | 3.0312 | 141.58 | 120.66 | 26.80000 | 22.32014 | 54.35519 | 114.85060 |
| B2-F4 | 3.0312 | 141.58 | 147.15 | 26.66100 | 22.15430 | 53.95160 | 115.07948 |

**Table 7 Initial Design - Calculations for Type 1 Series Blower (TEM3)**

| Blower-Fan Combination | Blower Air Flow (CFM) | Cold Plate Pressure Drop (Pa) | Fan Air Flow (CFM) | Cold Plate Exit Temp (°C) | TEC Temp (Cold Side) (°C) | TEC Temp (Hot Side) (°C) | Heat Diss. From Hot Side (W) |
|---|---|---|---|---|---|---|---|
| B1-F1 | 2.4135 | 89.76 | 88.30 | 25.68000 | 22.83701 | 54.43245 | 99.99277 |
| B1-F2 | 2.4135 | 89.76 | 108.89 | 25.50700 | 22.64379 | 53.99659 | 100.12163 |
| B1-F3 | 2.4135 | 89.76 | 120.66 | 25.43000 | 22.55779 | 53.80259 | 100.27807 |
| B1-F4 | 2.4135 | 89.76 | 147.15 | 25.29000 | 22.40142 | 53.44987 | 100.46800 |
| | | | | | | | |
| B2-F1 | 3.0312 | 141.58 | 88.30 | 29.29500 | 25.29692 | 54.53030 | 102.20023 |
| B2-F2 | 3.0312 | 141.58 | 108.89 | 29.14600 | 25.11914 | 54.09007 | 102.46347 |
| B2-F3 | 3.0312 | 141.58 | 120.66 | 29.08000 | 25.04040 | 53.89506 | 102.71668 |
| B2-F4 | 3.0312 | 141.58 | 147.15 | 28.95700 | 24.89365 | 53.53165 | 102.84960 |

Figure 13 shows variation of cold plate exit temperature with hot side fan with different thermoelectric modules.

### Initial Design Analysis – Blower Type-1

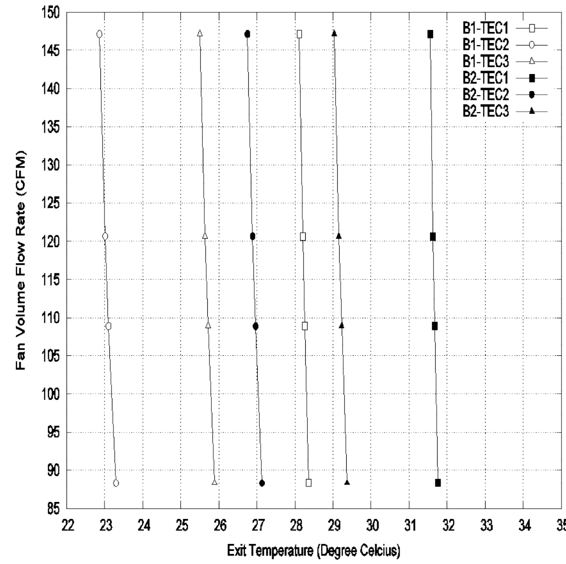


Figure 13 Initial Design - Exit Temperature vs. Fan Volume Flow Rate (Type 1).

### Calculations for Second Blower Series (Type 2 Series) Blower Characteristics

Table 8 shows values for the points chosen on blower (Type 2) characteristics curve as given in Fig 14.

**Table 8 Initial Design - Blower (Type 2) Second Series Characteristics**

| BLOWER | VOLUME FLOW RATE (CFM) | PRESSURE DROP (Pa) |
|---|---|---|
| Type 2/12 (B1) | 4.4145 | 300.29 |
| Type 2/12H (B2) | 4.7675 | 350.23 |

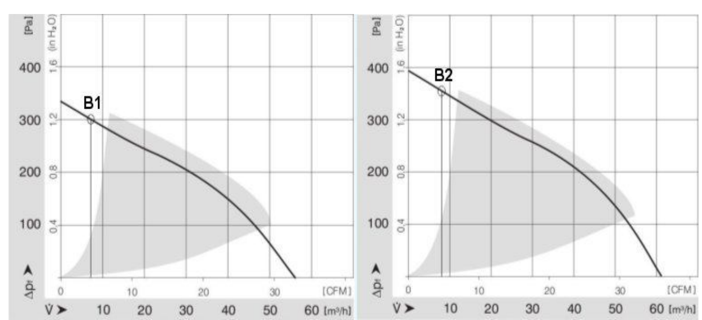


**Figure 14 Initial Design - Volume Flow Rate Selection for Second Blower Series (Type 2)**

### Cold and Hot Side Calculations for different Thermoelectric Modules

The tables 9, 10 & 11 show cold and hot side analysis for TEM1, TEM2 and TEM3 respectively with Second Series blower (Type 2).

**Table 9 Initial Design - Calculations for Second Series (Type 2) Blower (TEM1)**

| Blower-Fan Combination | Blower Air Flow (CFM) | Cold Plate Pressure Drop (Pa) | Fan Air Flow (CFM) | Cold Plate Exit Temp (°C) | TEC Temp (Cold Side) (°C) | TEC Temp (Hot Side) (°C) | Heat Diss. From Hot Side (W) |
|---|---|---|---|---|---|---|---|
| B1-F1 | 4.4145 | 300.29 | 88.30 | 36.49180 | 31.84548 | 53.74012 | 84.37444 |
| B1-F2 | 4.4145 | 300.29 | 108.89 | 36.42000 | 31.74898 | 53.37451 | 84.53743 |
| B1-F3 | 4.4145 | 300.29 | 120.66 | 36.38800 | 31.70597 | 53.21156 | 84.69197 |
| B1-F4 | 4.4145 | 300.29 | 147.15 | 36.32900 | 31.62668 | 52.91112 | 84.77842 |
| B2-F1 | 4.7675 | 350.23 | 88.30 | 37.33000 | 32.52331 | 53.76224 | 84.87347 |
| B2-F2 | 4.7675 | 350.23 | 108.89 | 37.26000 | 32.42675 | 53.38233 | 84.73352 |
| B2-F3 | 4.7675 | 350.23 | 120.66 | 37.23200 | 32.38813 | 53.23037 | 85.18807 |
| B2-F4 | 4.7675 | 350.23 | 147.15 | 37.17600 | 32.31088 | 52.92644 | 85.22461 |

**Table 10 Initial Design - Calculations for Second Series (Type 2) Blower (TEM2)**

| Blower-Fan Combination | Blower Air Flow (CFM) | Cold Plate Pressure Drop (Pa) | Fan Air Flow (CFM) | Cold Plate Exit Temp (°C) | TEC Temp (Cold Side) (°C) | TEC Temp (Hot Side) (°C) | Heat Diss. From Hot Side (W) |
|---|---|---|---|---|---|---|---|
| B1-F1 | 4.4145 | 300.29 | 88.30 | 32.66800 | 26.70643 | 55.24964 | 118.42807 |
| B1-F2 | 4.4145 | 300.29 | 108.89 | 32.53500 | 26.52768 | 54.73960 | 118.73536 |
| B1-F3 | 4.4145 | 300.29 | 120.66 | 32.47500 | 26.44704 | 54.50950 | 118.91999 |
| B1-F4 | 4.4145 | 300.29 | 147.15 | 32.36600 | 26.30055 | 54.09149 | 119.15351 |
| B2-F1 | 4.7675 | 350.23 | 88.30 | 33.67500 | 27.48169 | 55.28157 | 119.14848 |
| B2-F2 | 4.7675 | 350.23 | 108.89 | 33.55000 | 27.30926 | 54.77288 | 119.56929 |
| B2-F3 | 4.7675 | 350.23 | 120.66 | 33.49250 | 27.22995 | 54.53889 | 119.69493 |
| B2-F4 | 4.7675 | 350.23 | 147.15 | 33.39000 | 27.08856 | 54.12176 | 120.03495 |

**Table 11 Initial Design - Calculations for Second Series (Type 2) Blower (TEM3)**

| Blower-Fan Combination | Blower Air Flow (CFM) | Cold Plate Pressure Drop (Pa) | Fan Air Flow (CFM) | Cold Plate Exit Temp (°C) | TEC Temp (Cold Side) (°C) | TEC Temp (Hot Side) (°C) | Heat Diss. From Hot Side (W) |
|---|---|---|---|---|---|---|---|
| B1-F1 | 4.4145 | 300.29 | 88.30 | 34.39300 | 29.02477 | 54.69236 | 105.85614 |
| B1-F2 | 4.4145 | 300.29 | 108.89 | 34.27600 | 28.86752 | 54.23497 | 106.09351 |
| B1-F3 | 4.4145 | 300.29 | 120.66 | 34.22300 | 28.79629 | 54.02777 | 106.21639 |
| B1-F4 | 4.4145 | 300.29 | 147.15 | 34.12800 | 28.66862 | 53.65639 | 106.48231 |
| B2-F1 | 4.7675 | 350.23 | 88.30 | 35.30450 | 29.72938 | 54.72073 | 106.49616 |
| B2-F2 | 4.7675 | 350.23 | 108.89 | 35.19400 | 29.57696 | 54.26217 | 106.77494 |
| B2-F3 | 4.7675 | 350.23 | 120.66 | 35.14400 | 29.50799 | 54.05468 | 106.92581 |
| B2-F4 | 4.7675 | 350.23 | 147.15 | 35.05400 | 29.38385 | 53.68119 | 107.20450 |

Figure 15 shows variation of cold plate exit temperature with hot side fan with different thermoelectric modules.

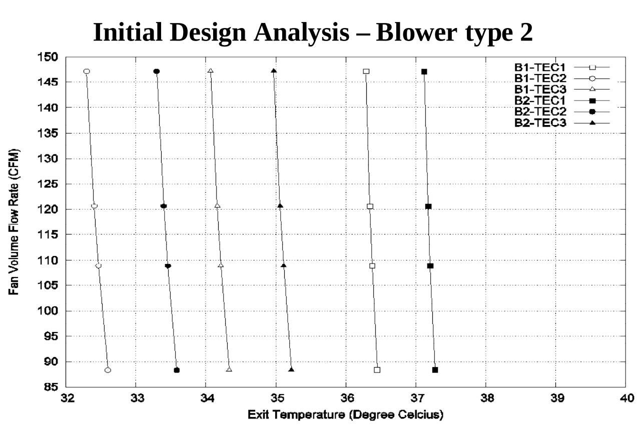


**Figure 15 Initial Design - Exit Temperature vs. Fan Volume Flow Rate (Second Series of Blower, Type 2)**

## 5. CONCLUSION

A systematic comparative study on performance of thermoelectric cooling system is performed. The flow and thermal patterns are predicted through CFD for initial calculations for cold plate designs. These calculations are then used to predict hot side system performance for different combinations of blowers, hot side fans and thermoelectric modules.

We find that using the combination of components available for design, it is possible to get cooling system to perform to obtain either very low exit temperature or very high flow rate

The above conclusion is visible from the graph shown in figure 16, where relationship between volume flow rate & cold plate exit temperature is evident.

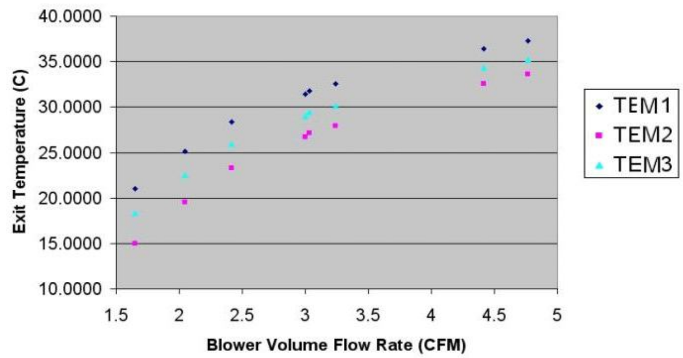


**Figure 16 Effect of Blower Volume Flow Rate on Cold Plate Exit Temperature**

The validation of 3D modeling & simulation was conducted by series of experiments at hot human climatic chamber. The experimental results are also very close to our simulation results.

It is also observed that the worker using these helmets was feeling much comfortable even at very high temperature i.e. at around 50 $^{o}$C ambient. When the body's natural cooling mechanism are ineffective, cold air circulating helmet is the better choice for creating a cool 'microclimate' to isolate the head from heat.

## 6. EXPERIMENTAL VALIDATION AND DISCUSSION

This 3D modeling & simulation is also validated by our prototype based on experimental results. On based on our simulation result we design and fabricate protype of backpack based cooling system and found that the simulation result in line with our experimental outcome of system. Figure 17 is the typical Lab Trial photograph of Back-pack Thermoelectric Cooling system and helmet at our Laboratory.

**Figure 17: Typical Lab-Trial Photograph by a person using back-pack Thermoelectric Cooling helmet at hot environment**.

In our present prototype we have used two TEM-2 thermoelectric modules connected in parallel on one side of the cold plate combined with Type 1/12(B2) blower, whose volume flow rate is 3.0312 CFM & pressure drop is 141.58 Pa and DC Axial hot side fan 4412H(F4), whose volume flow rate 147.15 CFM. Assembled system connected with safety helmet over the head is shown in figure 17. The DC power of the system was provided by Lithium-ion rechargeable battery (Ultralife), 4SIPX3 (2.9Ah), voltage range from 12V DC – 16.8V DC, Normal Capacity 8.7 Ah, Maximum discharge current 10A and weight 590 gms. Total weight of such system was 4.96 Kgs, but there was no extra load on Head.

Experiment was conducted at our hot human climatic chamber, where the average ambient temperature was raised up to 55°C with ± 5 °C. Temperature was controlled by series of temperature controllers. Relative humidity and wind speed were also controlled.

The ambient temperatures, hot side fin temperatures and exit air temperature from the helmet were recorded by fixing thermo-junctions of 14 channel ADAM-4018 temperature scanner placed inside the hot chamber.

Three thermocouples (named $T_1$, $T_2$ & $T_3$) were fixed on three exit air path inside the helmet to measure the actual air flow temperatures across the head and face of the human.

Another three thermocouples (named $T_4$, $T_5$ & $T_6$) were placed on the tips of the hot side fins to measure the fin temperatures i.e. heat dissipation temperatures.

Eight thermocouples (named $T_7$, $T_8$, $T_9$, $T_{10}$, $T_{11}$, $T_{12}$, $T_{13}$ & $T_{14}$) were placed randomly across the hot chamber to take the average hot chamber profile at every 10 seconds. Thermocouples of the above scanner were T-type (Copper / Copper-nickel) welded tip T/C wire, RS, Model: 219-4696 and the scanner was connected to a Dual Core PC, Make – HCL, Sr. No. B076A4074837.

First set of experiment was conducted at normal ambient temperature for 6000 seconds where the exit air temperature from the helmet was measured 28 °C – 30°C with an average ambient 40°C.

Figure 18 shows the results of Back-pack cooling system with helmet at normal ambient conditions.

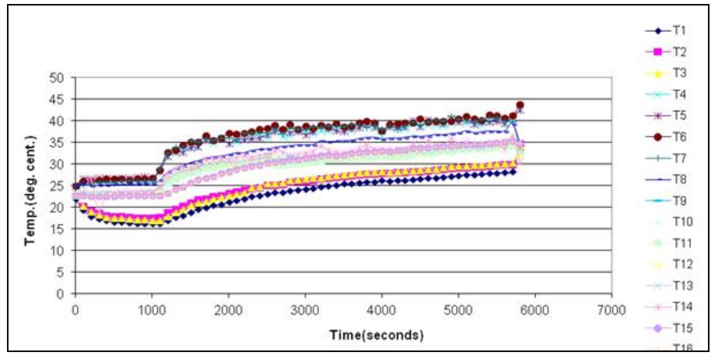


**Figure 18 Testing of Back-Pack Cooling system with helmet at normal ambient condition.**

Second, third and fourth sets of experiment were conducted at high ambient temperature with duration approximately 3500 seconds, 3000 seconds & 3000 seconds. It was observed that at hot chamber experimentation, the average exit air temperature from helmet over head & face of human was 41°C, where the average hot side fin temperature was 56°C and average ambient temperatures were 50°C–52°C. Figure 19, Figure 20 and Figure 21 are the typical results of experiment at hot chamber, were $T_1$, $T_2$ and $T_3$ shows three exit air temperatures from helmet, $T_4$, $T_5$ and $T_6$ shows the hot side fins temperatures and $T_7$ to $T_{14}$ shows randomly placed hot chamber temperatures.

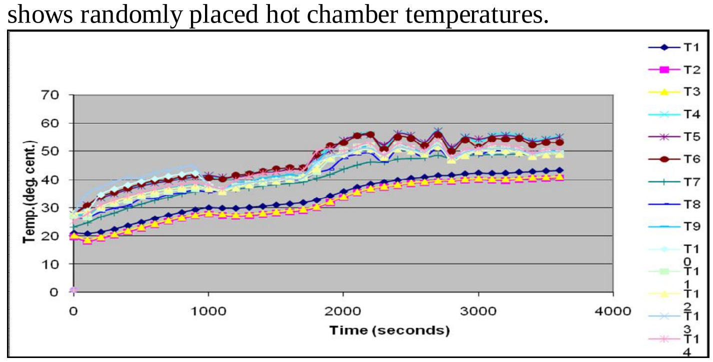


**Figure 19 Testing of Back-Pack Cooling system with helmet at hot human climatic chamber.**

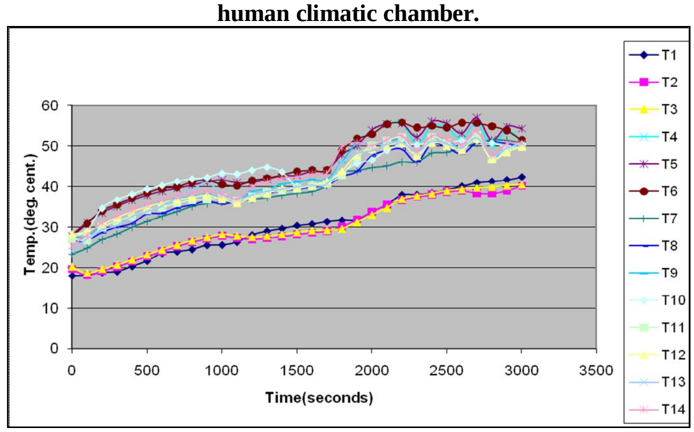


**Figure 20 Testing of Back-Pack Cooling system with helmet at hot human climatic chamber.**

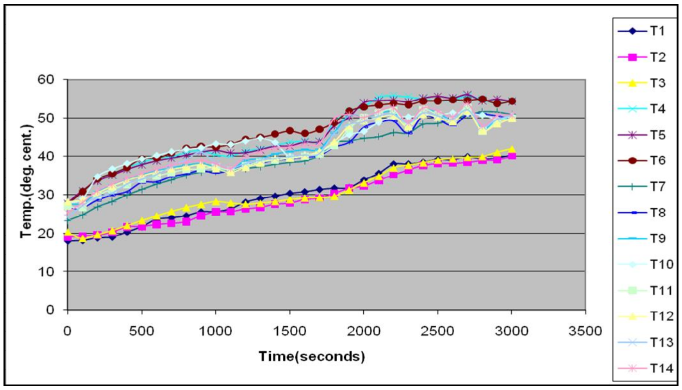


**Figure 21 Testing of Back Pack cooling system with helmet at hot human climatic chamber.**

From the experimentation; it was observed that the person used such cooling helmet at hot environment were feeling much comfortable. The reasons of feeling comfortable may be analysized as follows:-

i. The average exit temperature over head & face of the person was 41$^{o}$C, which was lowered than 10 to 11$^{o}$C from the ambient.

ii. Air was blowing through head & face at 52$^{o}$C, which evaporated sweat from the skin and provide additional cooling mechanisms.

The above two logic might be the reasons for feeling much comfort at hot environment, which normally excel at maintaining correct body temperature and blood flow through the skin.

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