Optimal Design of an Air-Cooling System for a Li-Ion Battery Pack in Electric Vehicles with a Genetic Algorithm

Mohsen Mousavi, Shaikh Hoque, Shahryar Rahnamayan, Ibrahim Dincer, Greg F. Naterer

Faculty of Engineering and Applied Science, University of Ontario Institute of Technology (UOIT)
2000 Simcoe Street North, Oshawa, Ontario L1H 7K4, Canada

(mohsen.mousavi@uoit.ca, shaikh.hoque@uoit.ca, shahryar.rahnamayan@uoit.ca, ibrahim.dincer@uoit.ca, greg.naterer@uoit.ca)

Abstract. **This paper examines and optimizes parameters that affect the air cooling of a Lithium-Ion (Li-Ion) battery, used in Electric Vehicles (EVs). A battery pack containing 150 cylindrical type Li-Ion battery cells in a PVC casing is investigated. An equal number of tubes are used in the pack as a medium to cool the battery by using a fan when the vehicle is stationary or with ambient air when in motion. The parameters affecting the air cooling of battery are studied and optimized by considering their practical constraints. The objective function and Number of Transfer Unit (NTU) are developed. Finally, a genetic algorithm method is employed to optimize the decision variables. Analysing the results shows that NTU can be maximized by increasing the diameter of tubes on the battery and keeping the air velocity in a certain range.**

Keywords: EV, Thermal Management, Li-ion Battery, Air Cooling, Genetic Algorithm, Optimization

I. INTRODUCTION

One of the most serious issues in the 21st century is how to address the increasing demand for energy and the environment. As for carbon dioxide emissions, as an example among others, it has been increased by up to five times during the past century, and its concentration is rapidly increasing. In terms of oil consumption by sectors, the transportation sector consumes more than half of the total amount, therefore, an improved fuel economy of vehicles is required in order to reduce carbon dioxide emissions for coping with this global environmental issue. Consequently, electrified vehicles such as electric vehicles (EVs), hybrid electric vehicles (HEVs), and fuel cell hybrid electric vehicles (FCHEVs) are expected to be key technologies to address these issues.

Lithium-ion is a source of energy for the Electric vehicles. Cooling of the Li-ion batteries has been the focus of researchers and automotive manufacturers in the past few years as a major obstacle for the development of EVs. A main challenge is the thermal management associated with Lithium-ion batteries. An excessive local temperature rise in Li-ion batteries causes a reduction of cycle life and may lead to "thermal runaway" of an individual cell or entire battery pack. In the battery pack, where the cells are closely packed, in order to exploit the advantage of Li-ion's high energy and power density, thermal runaway of the cells propagates and causes the entire battery to fail violently. More frequently, an excessive or uneven temperature rise in a module or pack reduces its cycle life significantly. However, for commercial applications, it is important to not overdesign the cooling system and unnecessarily complicate the control hardware. Hence interest is emerging in active thermal management, that is, a cooling system which requires a blower and air flow distribution to maintain the temperature and battery thermal profile within a desired range.

The main objective of this paper is to provide a background review of electric vehicles and Li-Ion batteries, along with air cooling systems. It also discusses the battery design parameters and a heat transfer model developed for thermal management and optimizing the model. Some corresponding fitness functions, decision variables, and constraints are introduced, and optimization results are presented with some examples.

II. ELECTRIC VEHICLES AND LI-ION BATTERIES

Electric vehicles are propelled by the electric motor drive, using a battery, and ultra-capacitor as Energy Storage. The battery is charged by the electrical grid charging facilities. Electric vehicles have zero greenhouse gas emissions during operation and they may have a high energy efficiency. The major drawback for Electric vehicles are battery sizing and heat management challenges, lack of charging facilities, low battery lifetime, and high cost of vehicles [1]. Fig. 1 shows a high level architecture of an electric vehicle. An inverter is used to convert the DC to variable voltage and variable frequency to power the propulsion motor. An ultra capacitor is generally used to provide supplemental power and for starting the system. Ultra-capacitors, also known as super-capacitors or electrochemical capacitors, utilize high surface area electrode materials and thin electrolytic dielectrics to achieve capacitances several orders of magnitude larger than conventional capacitors. In this way, ultra-capacitors are able to attain greater energy densities while still maintaining the characteristic of high power density of conventional capacitors [2].

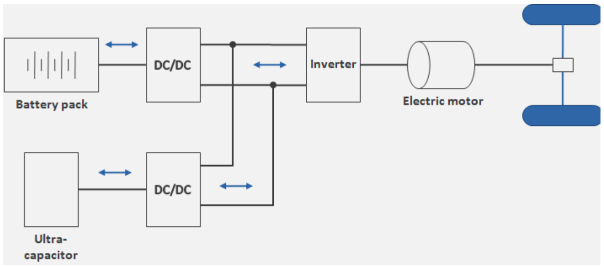

Figure 1: Configuration of an EV with a battery pack and ultra-capacitor *(Li et al., 2009)*

Li-ion batteries provide an attractive alternative to other battery chemistries, due to high energy storage density and competitive cost. However, Li-ion batteries generate significant heat during high power discharge. A Li-ion battery has a nominal cell voltage of 3.7 volts compared to 1.4 volts in Nickel Metal Hydrides and 2.1 volts in Lead Acid batteries, which translates to significant energy density. Also Li-ion batteries have a much wider operating temperature range compared to Nickel Metal Hydrides [3]. Depending on the battery's chemistry, the surface temperature of a battery pack can rise up to 90°C after 10 minutes of battery operation in charging or discharging modes. HHowever, the temperature of the Li-ion battery must be regulated within the optimum range, failure of which can adversely affect the electrochemical performance of Li-ion cell charge acceptance, power and energy capability, reliability, cycle life, safety and cost. The operation of most Li-ion cells is limited to a temperature of 20°C to 40°C [16] , in which, heat generation, due to internal resistance and polarization, is easily controllable by working with the voltage window and range of charge/discharge rates recommended by the manufacturers. Harsh conditions, such as operation at high temperatures, steeply accelerate the accumulation of thermal energy in Li-ion cells [4]. On the other hand, air cooling of a battery creates a high potential for energy savings and heat recovery. This can be done by removing heat from the battery and using it as a heat source to warm up the vehicle cabin during cold weather conditions. A typical Li-ion battery, used in electric vehicles, weighs over 300 kg for a compact size vehicle. Considering the battery's high temperature during its operation, the energy savings potential is significant.

III. EXISTING TECHNOLOGIES FOR LI-ION BATTERY COOLING

The goal of a thermal management system in an EV is to maintain an acceptable temperature range for a battery pack (dictated by life and performance trade-off) with a uniform temperature distribution (or only small variations between the modules and within the pack) as identified by the battery manufacturer. A thermal management system may use air for heating, cooling, and ventilation, liquid for cooling / heating, insulation, thermal storage such as phase change materials, or a combination of these methods. The thermal management system may be passive (only the ambient environment is used) or active (special components provide heating and cooling at cold or hot temperatures) [4-6].

In active air cooling, the battery will be cooled by passing air into the air channels that will be designed inside the battery pack. The air with lower temperatures can cool down the battery. The rate of heat removal depends on many factors including the battery chemical and physical structure, rate of heat generation that in turn depends on the usage of the battery based on powertrain demand, HVAC demands including heating and cooling loads, lighting demands, etc.

In this study, active air cooling of a Li-ion battery has been considered as a cooling option. The outside air will be drawn into the vehicle by a centrifugal fan when the vehicle is idling (not moving). The fan is a high consumer of energy and one of the main goals is to minimize power consumption of the fan in this study. The fan may not be needed when the vehicle is in motion, as the outside air will pass though the Air-Inlet-Panel, inside the HVAC ducting system that can in turn be directed to the battery. In that case, its velocity will be managed by air dampers.

IV. BATTERY DESIGN PARAMETERS

There are many different types of Li-ion batteries that can be used for automotive power applications. In this paper, a cylindrical type Li-ion battery cell has been considered. Fig. 2 illustrates the structure of a cylindrical Li-Ion Battery.

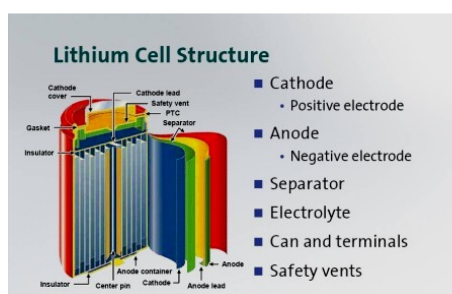

Figure 2: Structure of a Li-Ion Battery *(source: GM , 2007)*

As mentioned earlier, Li-ion batteries are heated during vehicle operation. Battery chemistry has an essential role in the level of temperature that a battery can tolerate without performance degradation or loss of function. Parameters in the battery design including the overall dimensions, tube sizes and their orientation, number of tubes, and whether rough or smooth, can significantly affect the heat transfer rate. These parameters are studied and optimized for the best heat transfer result and consideration of design manufacturability.

Today's Li-ion battery pack for compact electric vehicles has a volume that ranges from 80,000 to 100,000 cubic centimetres or 80-100 litres. The dimensions of a battery that has been used for this study are L=1.25 m, W=1.0 m and H=0.325 m. The battery pack has 150 Li-ion battery cells. The diameter of these batteries can vary depending on the power density of the battery. For a higher power density, there is a lower diameter. A higher density battery cell costs more than a lower power density. To cool the battery, we will design 150 tubes inside the battery to cool the battery when air passes through them. The objective of the design is to have a diameter of air channels as small as possible such that there will be more space to package the battery cells with larger diameters. Fig. 3 shows the battery pack that has been designed and analyzed in the current study.
Fig. 4 shows the battery with cells that are located among the tubes. The cells will be designed longitudinally in the direction of air flow

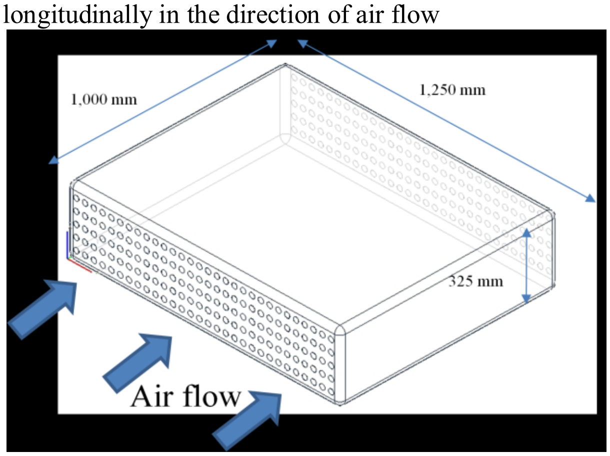

Figure 4: Battery designed with tubes to increase the heat transfer rate

Packaging of Battery Pack. There are many different packaging options to place the Battery Pack inside the vehicle. Packaging of a Lithium Ion Battery is a decision that is mainly driven by the vehicle safety. Most manufacturers place the battery pack at the rear of the vehicle, i.e., trunk or underneath the rear seats, and in the middle of a vehicle surrounded by many structural elements. In the current analysis, it is assumed that the battery can be safely packaged in the front of a vehicle under the hood. This type of design helps the air flow from the Air-Inlet–Panel to the battery pack, thus reducing the fan usage, Fig. 5.

Tube roughness. The interior surface of a tube is considered smooth in this study. Tube surfaces are often roughened, corrugated, or finned in order to enhance convection heat transfer. The amount of heat transfer in turbulent flow in a tube can be increased by as much as 400% by roughening the surface [7]. Roughening the surface also increases the friction factor and thus the power requirement for the fan. The trade-off in this case should be evaluated. The cells' surface temperature will remain nearly constant and it reaches a peak temperature of 90°C. This will be helpful to design the cooling system such that it can handle the worst case scenarios as well.

Battery pack cooling fan design. To avoid extra cost and less power consumption, the same fan used for the HVAC system can be used to cool down the battery. The analysis will calculate the fan velocity required for a small car that is the same size of car as used for a battery design and minimum requirement for the battery cooling fan.

*Vehicle Air Change Number (ACH), CFM and air velocity calculations***.** An assumption is to design the air exchange rates or air changes per hour (ACH) ranges between 1.0 and 3.0 per hour with windows closed and

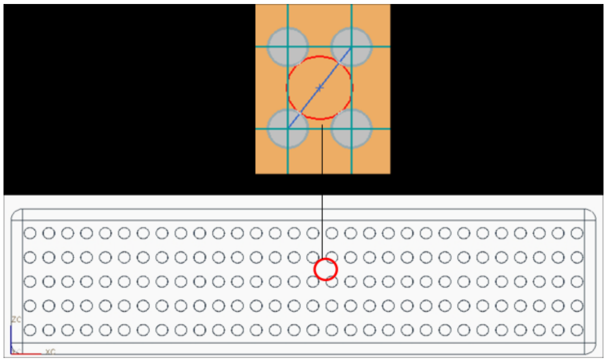

Figure 4: Li-ion battery cells located around the tubes

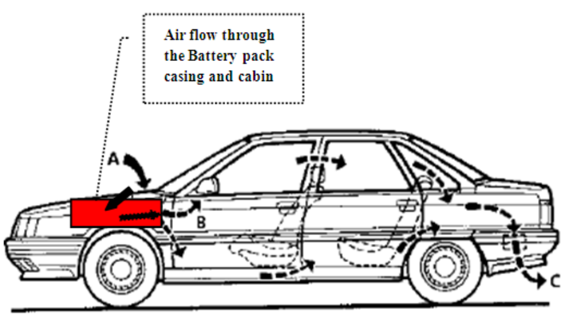

Figure 5: Battery pack located in the front of a vehicle for increased effectiveness of heat transfer

no mechanical ventilation, between 1.8 and 3.7 per hour for windows closed with a fan set on recirculation, between 13.3 and 26.1 per hour for windows open with no mechanical ventilation, and between 36.2 and 47.5 per hour for a window closed with the fan set on fresh air. ACHs for windows closed with no ventilation will be higher for the older automobile than for a newer automobile [8]. As mentioned earlier, it is assumed that the fan is set to fresh air and ACH is assumed to be 40 in this case. The cabin volume for small to midsize cars ranges from 2-3.5 m3 [9]. Assuming 2.5 m3 of cabin volume, the CFM of the system will be 59 based on 47.5 ACH at full fan speed. The air velocity can be obtained by

$$V = \frac{\dot{m}}{\rho.A} \quad (1)$$

where V is the air velocity (m/s), $\dot{m}$ is mass flow rate of air in the vehicle HVAC ducts (kg/s), ρ is air density (kg/m^3, variable with air temperature, constant in this case study) and A is the duct area (m^2) at a specified active zone (e.g. windshield defrost zone, front of dash ventilation ducts, etc.).

Assuming a total active duct area of 0.03 m^2 inside the vehicle, at a desired cabin temperature of 20°C, the air density will be 1.204 kg/m^3. Hence the air mass flow rate will be 0.0395 kg/s at the calculated CFM. Therefore the maximum air velocity through the ducts can be calculated by equation (1), which yields V = 0.47 m/s. This figure will be used as the minimum air velocity of the battery cooling fan.

Power consumed by electric fan. At higher speeds, the air entering the vehicle AC system will be sufficient for the required ventilation. However, when the vehicle is not moving or moving at a slow speed, an electric fan is required to transfer heat from the battery pack to draw outside air. The power consumed by the electric fan is deducted from heat obtained by the battery to obtain the net heat gain. The power used by the electric fan is a function of the fan's CFM. The power rating of centrifugal fans in the vehicle is approximately 4 Watts per CFM. Using the CFM of the electric fan, the power usage of the fan will be 256 W. This amount will increase significantly as the power demand for cooling the Battery pack increases.

V. CONVECTIVE HEAT TRANSFER MODEL

To analyze the heat transfer, the following assumptions are made: (i) radiation heat transfer is negligible, (ii) temperature differences between a battery cell's surface and cooling surface of the enclosure is negligible, (iii) surface temperature of the battery (Ts) is constant and at its maximum limit of 90°C, (iv) ambient temperature effect on the battery cell temperature is neglected, (v) air density remains constant at all temperatures, (vi) no heat transfer from the surface of a Battery Pack, and (vii) battery surface convective heat transfer is negligible.

Heat flux calculations. The convective heat transfer for flat surfaces of the battery pack can be expressed as

$$\dot{Q}_{conv} = hA_S(T_S - T_\infty) \quad (2)$$

where h, and Ts and T∞ denote the convective heat transfer coefficient, surface temperature, and ambient temperature, respectively. The convective heat transfer in the tubes, using an arithmetic mean temperature difference, can be expressed as [7]:

$$\dot{Q}_{conv} = hA_S\Delta T_{avg} \quad (3)$$

with

$$\Delta T_{avg} = T_s - \frac{T_e + T_i}{2} \quad (4)$$

Here, T_e is the exit temperature of the pipe and T_i is the inlet temperature. It is important to know that T_s may vary with location, and h may be a function of both location and temperature, however, for simplicity in this case, they are considered uniform. As mentioned in the assumptions, T_s is assumed to be constant, and in the steady state, the battery and maximum current draw T_s will be 90°C. Also, A_s is the interior area of the tubular surfaces and defined as

$$A_{s,\ tubes} = 150*(D*3.14) = 471*D \quad (5)$$

where D is tube diameter, which to be optimized in this study. To calculate the convective heat transfer coefficient h from the surface of the battery to the ambient air, the following steps are taken:

Reynolds number. The Reynolds number is defined as

$$Re_x = \frac{VL}{\nu} \quad (6)$$

where V is the air velocity (m/s) on the surface of the battery (m/s), L is characteristic length of the surface (m) and ν is the kinematic viscosity of air (m/s). The Nusselt number Nu is calculated as follows:

$$Nu_x = \frac{h_x}{k} = 0.0296Re_x^{0.8}Pr^{\frac{1}{3}} \quad (7)$$

For $0.6 \le P_r \le 60$, $5 \times 10^5 \le R_{ex} \le 10^7$

where P_r is the Prandtl number.

Calculation of h based on Nusselt number. The next step is to calculate the heat flux from the tubular surface of the battery. The steps are similar to the case of heat transfer from the surface. For the Reynolds number (*Re*), the characteristic length will be the diameter of tubes. For the case of a tube, the friction factor has an important role in the heat transfer. The friction factor is obtained by the Petukhov equation as

$$f = (0.790 lnRe - 1.64)^{-2} \qquad (8)$$
$$3000 \leq Re \leq 5 * 10^{6}$$

The Nusselt number in this case can be obtained from the Chilton-Colbum analogy [7] as

$$Nu = 0.125 f Re P_r^{1/3} \qquad (9)$$

where f indicates friction factor of the interior tubes walls, Re is the Reynolds number and P_r is Prandtl number.

Number of Transfer Unit (NTU). An important aspect of tubular heat transfer is the NTU, which is the Number of Transfer Units. NTU is a measure of the effectiveness of the heat transfer system. For NTU = 5, T_e = T_s and the limit for heat transfer is reached. A small value of NTU indicates more opportunities for heat transfer. NTU is calculated as follows:

$$NTU = \frac{hA_s}{\dot{m}c_p} \qquad (10)$$

where NTU is number of transfer unit, h is heat transfer coefficient, A_s is effective heat transfer area, $\dot{m}$ is mass flow rate and c_p is specific heat capacity.

An example of an NTU calculation with a tube diameter of 1 inch is shown in Table 1. NTU in this case is less than 2. The exit temperature of the tube is much higher than the inlet temperature.

VI. Genetic Algorithm To Maximize NTU

A Genetic Algorithm (GA) is an evolutionary optimization algorithm to solve multi objective nonlinear problems. An initial population is generated randomly, in such a way that each chromosome represents a possible solution to a given problem. Each chromosome is assigned a fitness value based on how well it fits given conditions. Each chromosome is evaluated by the fitness function which is determined subsequently.

Table 1: Calculation of NTU and heat flux values for 1-inch diameter tubes

Air Specific heat Cp j/kg.°C	**Air Mass flow rate in the tubes** Kg/s	**Air Thermal conductivity** k W/m.°C	**Air Kinematic viscosity** v m2/s	**Prandtl number** Pr	**Tube diameter** D m
1007	0.0395	0.02551	1.56E-05	0.7296	0.0254
1007	0.0395	0.02588	1.61E-05	0.7282	0.0254
1007	0.0395	0.02625	1.66E-05	0.7268	0.0254
1007	0.0395	0.02662	1.70E-05	0.7255	0.0254
1007	0.0395	0.02699	0.0000175	0.7241	0.0254
1007	0.0395	0.02735	1.80E-05	0.7228	0.0254
1007	0.0395	0.027715	1.85E-05	0.7215	0.0254
Air velocity V m/s	**Reynolds number** Re	**Friction Factor** f	**Nusselt number** Nu 0.125fRePr1/3	**Convection heat transfer coefficient** h W/m2.°C	**Heat transfer area** As m2
0.47	764	0.076957087	6.62	6.59	11.94
0.47	742	0.077945522	6.51	6.387	11.94
0.47	721	0.078945613	6.4	6.193	11.94
0.47	701	0.079936258	6.3	6.009	11.94
0.47	682	0.080938708	6.2	5.833	11.94
0.47	664	0.081932239	6.1	5.667	11.94
0.47	646	0.082937708	6.01	5.508	11.94
Battery surface temperature Ts °C	**Tube entrance temperature** Ti °C	**NTU**	**Tube exit temperature** Te °C	**ΔT** °C	**Heat Generated** Q W
90	-40	1.978207	23	80.1739	-6309
90	-30	1.917244	32	76.8609	-5862
90	-20	1.858912	43	73.547	-5438
90	-10	1.803745	54	70.2321	-5039
90	0	1.750792	62	66.9164	-4660
90	10	1.701245	74	63.5996	-4304
90	20	1.653365	83	60.2822	-3964

The generated chromosomes have the highest fitness value in the population. They have the highest probability to be selected as a member of parents to generate the next generation. They have the opportunity to be reproduced with another chromosome by a crossover operator, and producing decedents with both characteristics. Finally, mutation will happen to the chromosomes in a small probability given by the mutation operator.

A new population is therefore generated by three genetic operators. If the parameters of the GA, such as population size, selection probability, crossover probability, and mutation probability are selected properly, the population will converge to a best chromosome which represents the best solution for the given problem after some generations.

VIII. Fitness Functions, Variables And Constraints

In this study, the NTU equation has been developed with a variable air flow rate into the tubes and pipe diameter.

The fitness function becomes

$$NTU = \frac{hA_s}{\dot{m}c_p}$$

where

$$h = \frac{Nuk}{D}$$
$$Nu = 0.125 f Re Pr^{\frac{1}{3}}$$
$$f = (0.790 ln Re - 1.64)^{-2}$$
$$Re_x = \frac{VL}{\nu}$$

In this GA problem, the optimized values for V and D will be searched subject to the following boundary conditions:

$$0.0254 \le D \le 0.0508$$
$$0.4 \le V \le 10$$

where D is diameter of the pipe in meter and V is velocity of air in the cooling pipe is m/sec.

The following are other assumed known values for these equations:

$$P_r=0.7255,\ C_p=1007\ J/kg.°C$$
$$\nu = 0.17 * 10^{-4}\ m^2/s$$

where Pr is Prandtl number, C_p is the air specific heat capacity and ν is air kinematic viscosity.

IX. MATLAB GA TOOL SETTING

MATLAB GA tool is used to obtain optimized solution for the he fitness function as described earlier. The fitness function and constraints are discussed and decided in the above however to run the MATLAB GA algorithm and obtain optimal solution for the parameters a number of parameters need to be decided within the tool. These parameters are including but not limited to: population setting, fitness scaling setting, selection, reproduction, mutation, crossover, migration, algorithm settings and stopping criteria. [20]

Population setting: The population type for this study is considered to be 100. Matlab internal function is used to create the initial population i.e. constraint dependent default. Initial scores enable specifying scores for the initial population. In this study it is decided that the algorithm computes the scores using the fitness function. Initial range specifies lower and upper bounds for the entries of the vectors in the initial population. In this case the initial range will be similar to the constraints for the input parameters.

Fitness scaling: The scaling function converts raw fitness scores returned by the fitness function to values in a range that is suitable for the selection function. Scaling function specifies the function that performs the scaling. Matlab offers the following choices for scaling function: i) “Rank”scales the raw scores based on the rank of each individual, rather than its score, ii) “Proportional” makes the expectation proportional to the raw fitness score, iii) “Top” scales the individuals with the highest fitness values equally. v) Custom enables to write own scaling function. In this study the “Rank“ scaling function has been used that uses the highest rank of individual solutions in terms of fitness function value for selection of next generation.

Selection : The selection function chooses parents for the next generation based on their scaled values from the fitness scaling function. The following choices are available :i) “Stochastic uniform“ lays out a line in which each parent corresponds to a section of the line of length proportional to its expectation, ii) “Remainder” assigns parents deterministically from the integer part of each individual's scaled value and then uses roulette selection on the remaining fractional part. iii) ”Uniform“ selects the parents at random from a uniform distribution using the expectations and number of parents. This results in an undirected search. iv) Shift linear scales the raw scores so that the expectation of the fittest individual is equal to a constant, which can be specified as Maximum survival rate, multiplied by the average score. v) “Roulette” simulates a roulette wheel with the area of each segment proportional to its expectation. The algorithm then uses a random number to select one of the sections with a probability equal to its area. vi) “Tournament” selects each parent by choosing individuals at random, the number of which can be specified by Tournament size, and then choosing the best individual out of that set to be a parent. vii) Custom. In this study the “Roulette” selection has been chosen.

Reproduction: determine how the genetic algorithm creates children at each new generation. Elite count specifies the number of individuals that are guaranteed to survive to the next generation. Elite count will be set to a positive integer less than or equal to Population size. Crossover fraction specifies the fraction of the next generation that crossover produces. Mutation produces the remaining individuals in the next generation. Crossover fraction will be set to be a fraction between 0 and 1.

Mutation: make small random changes in the individuals in the population, which provide genetic diversity and enable the genetic algorithm to search a broader space. The following choices are available for Mutation functions: i) “Gaussian” adds a random number to each vector entry of an individual. This random number is taken from a Gaussian distribution centered on zero. ii) “Uniform” is a two-step process. First, the algorithm selects a fraction of the vector entries of an individual for mutation, where each entry has the same probability as the mutation rate of being mutated. In the second step, the algorithm replaces each selected entry by a random number selected uniformly from the range for that entry. iii) Adaptive feasible randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation.

iv) “Constraint dependent default“ that chooses “Gaussian” if there are no constraints and “Adaptive feasible” otherwise ; v) Custom. In this study the “ Uniform” type is used for “ Mutation” function. Uniform mutation refers to each gene of the chromosome which has a randomly generated probability to be replaced.

Crossover: combines two individuals, or parents, to form a new individual, or child, for the next generation. The following choices are available: i)” Scattered” creates a random binary vector. It then selects the genes where the vector is a 1 from the first parent, and the genes where the vector is a 0 from the second parent, and combines the genes to form the child, ii) “Single point” chooses a random integer n between 1 and Number of variables, and selects the vector entries numbered less than or equal to n from the first parent, selects genes numbered greater than n from the second parent, and concatenates these entries to form the child. iii) “Two point” selects two random integers m and n between 1 and Number of variables. iv) “Intermediate” creates children by a random weighted average of the parents. v) “Heuristic” creates children that randomly lie on the line containing the two parents vi)” Arithmetic “creates children that are a random arithmetic mean of two parents, uniformly on the line between the parents. vii) Custom. In this study a single point crossover will be used.

Migration: Migration is the movement of individuals between subpopulations, which the algorithm creates if Population size is set to be a vector of length greater than 1. Every so often, the best individuals from one subpopulation replace the worst individuals in another subpopulation. Migration can be controlled by “Direction” which migration can take place. If Direction is set to Forward, migration takes place toward the last subpopulation. That is the nth subpopulation migrates into the (n+1)th subpopulation. If direction is set to Both, the nth subpopulation migrates into both the (n–1)th and the (n+1)th subpopulation. “Fraction” controls how many individuals move between subpopulations. Fraction is the fraction of the smaller of the two subpopulations that moves. In this study the Direction is set to both, Fraction is set to 0.2 and interval is set to 20.

Stopping criteria: determines what causes the algorithm to terminate. In this study the maximum number of generation is set to 50, Stall generation is set 30 and the rest of option is set to MATLAB defaults.

IX. Numerical Results

The GA optimization toolbox of Matlab has been used with the above fitness function, variables and their box-constraints. The results are not exactly the same with the variation of GA parameters, but they're close to one another. Table 2 shows the Genetic Algorithm's numerical results.

The result suggests an upper limit for the tube diameter and air flow velocity of 2.559. The predicted NTU is 4.85 (out of 5) as compared to the NTU provided in Table 1.

Table 2 : Numerical results obtained by the MATLAB Genetic Algorithm toolbox

Total number of Runs	**Number of Iterations each Run**	**NTU value**	**Tube Diameter (m)**	**Air Velocity (m/s)**
10	51	4.85	0.05	2.559
Average	51	4.85	0.05	2.559

X. Conclusions

In this paper, a Li-ion battery was designed to be positioned in front of the vehicle dash panel. Longitudinal tubes were designed in a battery pack that provides a medium to pass the ambient air through the battery pack. The heat transfer model was developed for the design and an objective function was introduced, involving the NTU and variables of cooling, tube diameters, air velocity, as well as their limits. The genetic algorithm was utilized to optimize the objective function for decision variables within desired boundaries. The results show that the optimum value of NTU is obtained when tube diameters are at their upper limit and the air velocity is about 2.6 m/s for this specific design.

XI. Nomenclature

A	Surface area of heat transfer (m2)
ACH	Air Changes per Hour
Cp	Specific heat capacity (kJ/kg°C)
CFM	Cubic Feet per Minute
EV	Electric Vehicles
GA	Genetic Algorithm
f	Friction factor
h	Convective heat transfer coefficient (W/m)
k	Thermal conductivity (W/m°C)
H	Battery height (m)
L	Battery length (m)
Lc	Characteristic length of heat transfer surface
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
NTU	Number of transfer units

Pr	Prandtl number
ρ	Density (kg/m3)
tb	Ambient temperature (°C)
Ts	Temperature on the battery surface (°C)
T∞	Temperature of outside air (°C)
Re	Reynolds number
V	Air velocity (m/s)
ν	Air kinematic viscosity (m2/s)
W	Battery width (m)

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