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Development of evaporative intercooler heat exchanger for vehicle charge air enhancement using CFD simulation

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ABSTRACT

Nowadays, the concern of vehicle manufacturers towards improving engine performance, reducing fuel consumption and exhaust emissions that can cause the pollution of the atmosphere, concerns of strict emission pollution control regulations. Intercooler heat exchanger devices are used for engine charge air temperature improving for engine performance and emissions reduction. This paper introduces a new add-on technology of intercooler heat exchanger- (IHE) developed for utilizing in intake charge air density enhancement in engine combustion for better performance. Presenting a challenge in contributing a framework process for geometry designing development procedure for accurate and reliable scale design size of an air-vapour gas shell-and-tube IHE type, used refrigerant coolant medium. The process presents effective IHE in design time consumption, accurate in scale with higher performance and reliability operation in all environment weather due to reversibility system. A selected design geometry of 60 bunches of tubes with 7.53 mm inner diameter and 150 mm long placed. Effectiveness and design parameter geometry calculation are conditions of the IHE dependent relations of the shell size to tube length in condition of engine space availability control. Pressure drop and cooling capacity of IHE configuration design are proportional to the availability of design space or pressure drop control by the engine. Numerical and simulation results expressed a significant ability of IHE of 2–13 kW cooling load and process applicability for qualified design geometry configuration for selected IHE type. The developments present significant geometry flexibility design with the ability of cooling load or heating effect if reversible system, which offered multipurpose use in widely all vehicle types.

***Keywords**:* heat transfer; intercooler; shell-and-tube; evaporative heat exchanger; charge air.

INTRODUCTION

Nowadays, studies within the field of engine's intercooler heat exchanger (IHE) aimed for developing higher engine performance, higher power, lower emissions, less fuel consumption and efficient engine life operation. However, globally the increase of on-roads used vehicles nowadays become a serious critical issue which led to environmental pollution [1]. This effort involves thermal design researchers regarding IHE modules and optimization of module structures types for better innovation in heat transfer performance and reliability of use in all weather conditions, capability effects of cooling and heating with adjustability in use for all engine types.

Heat exchanger is a device that can efficiently transfer or exchange heat energy between media [2]. Either being used for cooling or heating a medium, by transferring energy within another medium, thermal heat transfer were conducted due to the variation of temperature difference. The transfer could be occurred by conduction, convection or radiation. Meanwhile, the coolant medium could be air, liquid or gas [3]. Air thermal performance has a direct impact on conversion efficiency and output power of the vehicle engine unit [4]. Field studies showed a significant influence of low ambient temperature on engine performance [5,6]. Manipulating the air temperature gave the best engine enhancement results [7,8]. Thus, the heat exchanger has become an important engine component to be integrated with the engine inlet air manifold, the IHE was seen to give a significant influence on engine operation [9]. Charge air cooling-(CAC) of engine inlet air temperature reduction, influence the air density and flow pressure property [10-12]. In a compressive intake air charge using a turbocharger and supercharger, the compression effect led to an increase in air temperature and pressure [13,14]. The rise in air charge temperature is not desirable for combustion, as the air density contains fewer oxygen molecules [15,16], leading to incomplete combustion and causing the engine cylinder temperature to rise, which leads to pre-detonation of the combustion [17]. Even though, most of the conventional designs utilized are using air or water as coolant medium [18]. Peiyong et al. [19]; they studied the influence of CAC on engine performance due to ambient low temperature, presenting a significant improvement in engine emission reduction and performance. The results introduced an idea about the importunacy of IHE. Thus, new IHE designs were presented. Vishwanath et al. [20]; they introduced air to air cooling IHE used for engine performance enhancement. Cuong et al. [21]; they presented the air to water IHE with the consecration of the size variation problem. Roberts [22]; in his experiment, combined integrated the air to air IHE with evaporative cooling coil, presenting the idea of thermal capacity enhancement. Wang et al. [23]; they designed the IHE by using thermoelectric solid surface presenting a new cooling technique. Optimizing the structure of the IHE designs resulted in various designs developed shapes with use of alternative mediums, depending on the cooling capacity and medium used for CAC inlet independence of the engine [24].

However, most of conventional IHE designs thermal performance did not reach lower than zero temperature influence, non-operational or non-influence at low engine speeds. That why designers working on IHE enhancement for better thermal influence performance and operational capability in all boundary conditions.

The goal of IHE improving for better thermal performance conversion is to enhance its cooling performance for lower temperature cooling [25] and operational in all conditions with flexibility geometry in use in any vehicle types. Introducing innovation of design framework flow process in control of availability and capacity parameter control in beneficial of time, cost and optimum geometry design scale required.

A design with optional capability of adoption in case of vehicle engine pre-design or exist engine development in case of available space control [26].

In this study, selective IHE design type is Shell-and-tube heat exchanger with the multi-tube straight pass, counterflow. Furthermore, the shell domain supplied by evaporative coolant medium from the vehicle air-conditioning system and the air flow through the tubes. Selecting the tube side for cooling the air refers to future technical maintenance concerns, ease of fouling tube surface cleaning and lower influence of pressure drop compared to shell domain. Thus, the IHE served as an evaporator air cooler with the capability of reaching the sub-cooling effect. This will help to increase the study range of CAC engine temperature influence.

Nowadays numerical simulation platforms applications presenting an accurate numerical approach simulation to real-world value in IHE designs, which presents higher solution accuracy [27], much reliable in obtaining calculation results. The geometry design was evaluated in the simulation application platform of ANSYS to simulate the flow behavior and cooling capability.

The objectives of this study are contributing an interactive design framework flow process for selected IHE type utilized in vehicle engines enhancement, which is accurate with short time identification of geometry parameters and dimensions for IHE designs. Conducting a 3-D design modelling depends on selective boundary conditions of engine capacity and cooling capability for modelling IHE, sustainable efficient design outcome from framework process flow, advanced affordable geometry, ease of installation and high thermal cooling capacity and the ability of system revers to heating in case if required with minimum pressure drop.

INFLUENCE OF CHARGE AIR COOLING- (CAC) ON ENGINE PERFORMANCE

The increase of ambient air temperatures nowadays and engine air charge density over manifold using compression devices, turbocharger and supercharger has led to a rise in intake manifold air pressure and temperature [28] as well as the effect on engine performance and fuel consumption, Such air property is not desirable for a complete engine combustion [29]. Thus, CAC becomes one of the best solutions for temperature reduction through intercooler units. Intercoolers are heat exchanger devices used for reducing air temperature and pressure over the manifold, which means more oxygen molecules density interring combustion chamber to mix with the fuel creating a better-enhanced mixture for better combustion. The previous study demonstrated a significant influence of CAC on engine performance parameters study on IHE designs. In turbocharged engines, IHE showed its influence in engine performance for better combustion, fewer fuel consumption and fewer emission [30].

Types of Intercooler

The influence of CAC was introduced through research development enhancement of new designs and patents of intercoolers heat exchangers. IHE designs geometry variation dependent of using application and cooling capacity. Geometry size and scale depending on space availability and thermal capacity cooling required [31]. Generally, IHE classified into three types depending on the coolant medium material used for cooling the air charge, such as gas, liquid and soled with the ability to combining them. Innovation within thermal researches will introduce new types. Design scale of geometry depends on cooling medium used, air cooled type IHE need larger surface cooling compare to cooled by water coolant, while the evaporative IHE type scale becomes the most smaller scale due to the thermal cooling capacity of the coolant. Most available IHE utilized in vehicles nowadays are air-air intercooler, air-water intercooler, air-evaporative intercooler, air-solid intercooler, and combined intercoolers. The coolant medium can be liquid pressurized gas like CO_2, R134x, R22 or propane, which expand and evaporate inside the IHE cooling zoon leading to subzero cooling effect [32].

Air-Solid intercooler, this type of IHE is using solid surface contact of the thermoelectric cooling generator. Heat transfer is between the CAC and the cooled surface of alloy thermoelectric. Size optimized with the capacity required, easy installation and effective in standstill or moving vehicle. The capacity compares to others is a lower cooling effect [23].

IHE selective consideration

General commercial types of IHE vary in use and cooling capacity with operation type. The influence of geometry shape and size implemented in engine CAC selective for qualified geometry of IHE depends on variable parameters as effective cooling capacity and operation type, which vary with boundary conditions and vehicle statues of cooling boundary flow, coolant temperature and the vehicle motion condition (vehicle speed). However, intercooler's used in most experimental are effective, but cannot afford a cooling effect in low vehicle speed and lower cooling temperature range in real live condition. The evaporative IHE challenged over those problems, it has a higher cooling capacity and reaches lower temperatures with the ability of working in minimum capacity at low vehicle speed [33]. Figure 1 shows the selection of IHE geometry and type dependent consideration for shell-and-tube IHE.

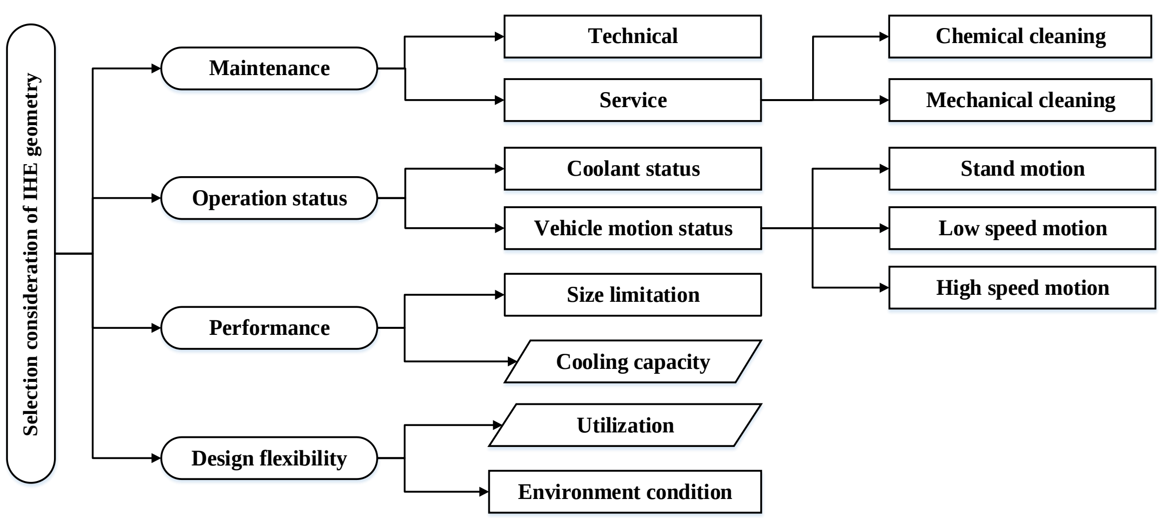


Figure 1. Selection consideration of qualified IHE used in CAC.

Performance of IHE
It is the cooling thermal capability and ability of IHE in cooling the CAC output temperature reduction. Selecting the right capacity to qualify with the engine size, engine space availability, which controls the IHE geometry scale size.

Operation status
It is the working condition of the IHE medium used, influencing the IHE performance and cooling range capability. The engine operation condition influences the selection of IHE, spicily at low engine speed, cold start or vehicle standstill operation.

Maintenance
Any add-ons part needs technical manufacturing and installation process, to integrate the IHE on the engine, influencing the IHE cost design and installation. The IHE working life depends on maintains service capability performance of the IHE. Cleaning facility influence the IHE life operation, in simple chemical surface cleaning and hard surface mechanical cleaning

Design flexibility
It is the ability to utilize the IHE for other purpose and variation engine types in all environmental condition.

PROPOSED WORK

The IHE technology has a significant thermal efficiency on the CAC engine system, which offers better engine performance and fuel consumption with fewer emissions [30]. The IHE reduces the compressed charged air volume, pressure and temperature, which make the oxygen density per volume higher [34] beneficial for better combustion burning, economical fuel consumption and reduction of exhaust emissions, economical fuel consumption and reduction of exhaust emissions. Thus, this technology provides the best achievement of performance enhancement solution. Development of IHE continues required. The selected design is a concept of evaporative IHE, which integrated into the manifold air intake system of an engine. The simulation study will investigate the thermal capability and velocity behaviour of the concept design cooling capacity, which operate on refrigerant R134a of the vehicle air-conditioning system. The adopted design is shell-and-tube heat exchanger type with multi-tube straight one pass, counter flow, the refrigerant medium coolant can be feed by the vehicle air-conditioning refrigerant or use independent refrigeration cycle. Selected geometry scale size optimized through the design framework flow process introduced.

Methodology
The selection of any geometry design requires technical issue to be considerate in design and manufacturing, Figure 2, shows a selective process consideration for the optimum geometry scale size of IHE in fit with a selective engine load or cooling load. The variation of options gave an opportunity for the designer to select the exact qualified IHE design. In option of control of is it predesign for future vehicle or design for an existing engine. Exit engine will parameter controller of the IHE scale and design type.

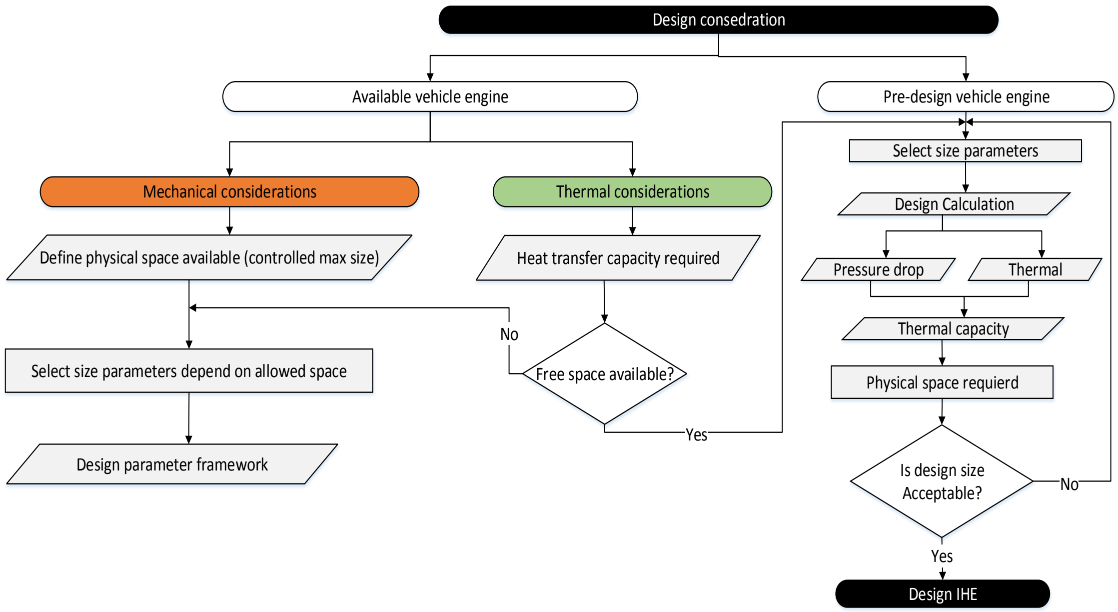


Figure 2. IHE Design consideration.

For the selective design, the selective data parameter selection for study analysis was assumed depending on previous literature selected for nominating engine or selecting load capacity. Sir Roberto [35]; in his investigation study, he used the size of 3 L four-cylinder four-struck engine run on 1000 to 3000 RPM, selected ambient temperature assumed at hot ambient environment temperature of 45℃, vehicle cooling thermal capacity at mentioned speed is 1.74 kW, refrigerant pressure is 2.8 bar. For designing optimum size IHE, the heat transfer area of IHE will be used as the optimizer of the design. The design process for obtaining the area of heat transfer optimized by using the heat transfer method or pressure drop method. Selected tube outside diameter is 9.53 mm inner 7.53 mm copper industrial size available in the market. The flowchart shows the selective parameter of IHE required size for a chosen cooling capacity, selecting variable dimensions, to conduct the best size desired by the user for a controlled parameter of the engine.

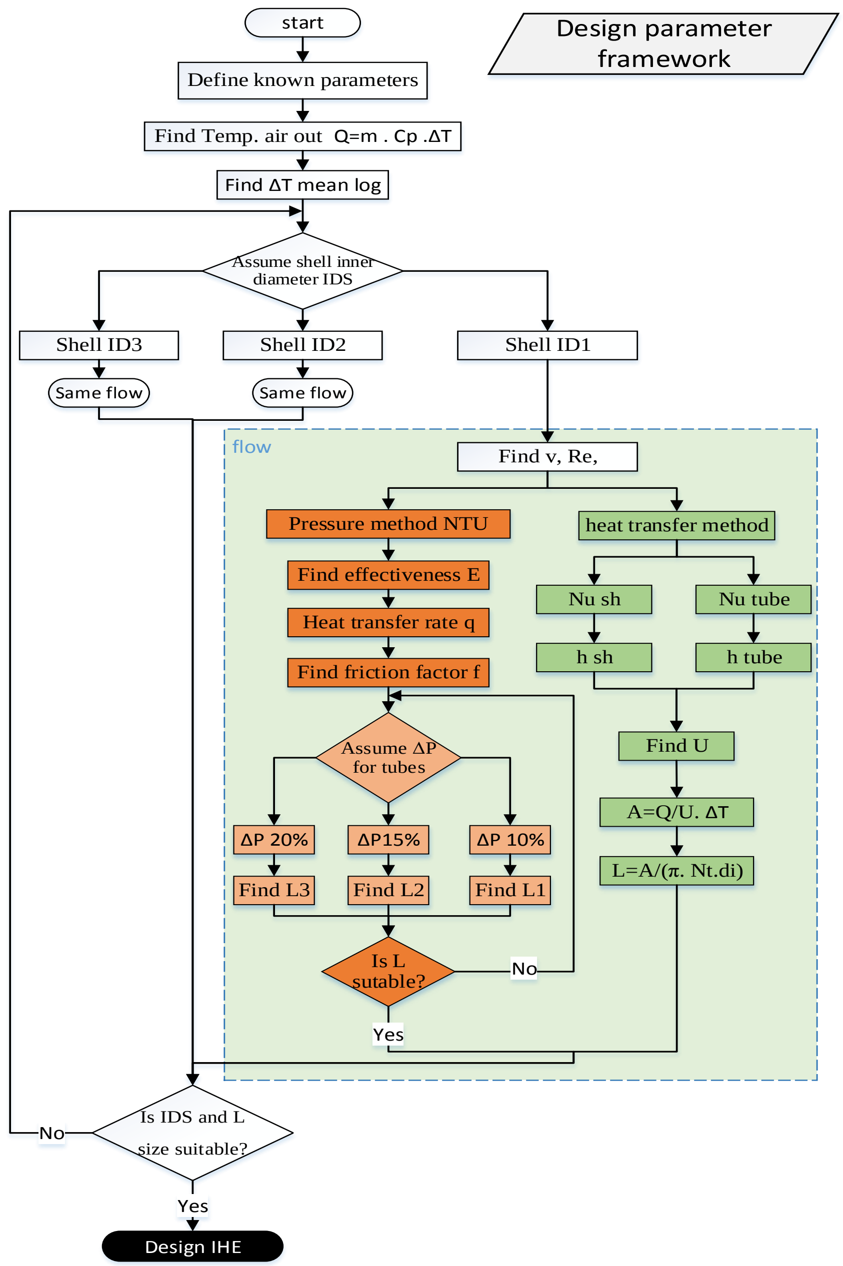


Figure 3. Design parameter framework

Framework schematic of the design process

The design process framework in Figure 3, is dependent on variable dimensions of Shell inner diameter (*Dsh.i*), assumed to obtain a suitable tube length for design the IHE, or can use pressure drop method to find the suitable tube length as second options when the designer search for minimum pressure drops, as if the pressure becomes dependent. The last step after obtaining the shell inner and tube length size is to design the IHE. The reversible design process, which IHE design shell scale is a dependent parameter to find the tube length.

CFM- cubic feet per minute m^3/s

For an engine, four cylinders four-struck gasoline spark ignition –SI, mass flowrate can obtain by Equation. (1).

$$CFM = (RPM/60) * 0.5 * (engine\ volume/1000) * \eta_V \tag{1}$$

where, RPM: is engine speed. Divided by 2, as one cycle is combustion, divided by 60 to convert from minutes to seconds. Size in L, to convert in to m^3, Engine size in Liter or Feet cubic, as 3L. η_V Engine volumetric efficiency, for non-turbocharge engines 0.8 and turbo charged engine is 2.

$$Q = v.A = \text{CFM} ===> \quad \dot{m} = \rho\,.\,v\,.\,A\ = \rho * Q \quad \text{kg/s} \tag{2}$$

Heat transfer method equations

Heat transfer rate: from energy heat balance theory, the amount of sensible heat transfer rate from the hot air by convection through the tube wall by conduction to latent heat coolant medium by convection are equals:

$$\dot{Q}_t = \dot{Q}_{ref} = \dot{Q}_a \tag{3}$$

$$\dot{Q}_t = U.A.\Delta T_{lm} \tag{4}$$

$$\dot{Q}_{ref} = \dot{m}_{ref}.\left(h_{ref.i} - h_{ref.o}\right) \tag{5}$$

$$\dot{Q}_a = \dot{m}_a.cp_a.(T_{a.i} - T_{a.o}) \tag{6}$$

Figure 4, shows the counter flow fluid in opposite directions, that there is two inlet and tow outlet flow with variable temperature. *ΔT* representing the result of hoot side flow subtract by cooled side flow to prevent negative value of temperature deference. Due to latent heat property of the refrigerant flow, temperature and pressure are constant. The method of Mean Logarithm of Temperature Differences (MLDT) evaluated:

$$\Delta T_{ML} = (\Delta T_1 - \Delta T_2)/(\ln(\Delta T_1/\Delta T_2)) \tag{7}$$

Overall heat transfer coefficient, [U] [W/m.2°C] for the new clean surface is

$$U = 1/\left(\frac{1}{h_a} + \frac{r_{t.o}\,.\ln\left(\frac{r_{t.o}}{r_{t.i}}\right)}{k_t} + \frac{1}{h_{ref\,.}}\right) \tag{8}$$

For tube layout with reasonable pitch selected as 2*$d_{t.o}$

Figure 5, is the IHE cross section shows the tube layout and heat transfer domain for both tube and shell side.

$$N_t = A_{sh}/\ (2.6\ A_t) \tag{9}$$

$$v_a = \frac{\dot{m}_a}{\left(\frac{\pi\,.d_i^2}{4}\right).\,\rho_a}\frac{N_p}{N_t} \tag{10}$$

$$A_{c.t} = \frac{\pi \,.\, d_i^2}{4} . \frac{N_t}{N_p} \tag{11}$$

$$Re_D = (\rho_a . v_{a.}\, d_i)/\mu_a = (\dot{m}._a \,.\, d_i)/(A_{c.t} . \mu_a) \tag{12}$$

$$f = (1.58 \ln(Re_D) - 3.28)^{-2} \tag{13}$$

Tube side (air flow)

$$Nu_t = \frac{h_a . d_i}{k_a} = \frac{(f/2).(Re_t - 1000) \,.\, Pr_t}{1 + 12.7\,(f/2)^{0.5} \,.\, (Pr_t^{2/3} - 1)} \tag{14}$$

$$h_a = (Nu_t . k_a)/d_i \tag{15}$$

Shell side (refrigerant flow)

$$\dot{m}_{ref} = \frac{\dot{Q}_{ref}}{h_{ref.o} - h_{ref.i}}$$

$$B = 74\, d_{t.o}^{0.75} \tag{16}$$

$$A_{c.sh} = (D_{i.sh\,.} C_{t\,.} B)/P_t \tag{17}$$

$$v_{ref} = \dot{m}_{ref} \,/\, (\rho_{ref} \,.\, A_{c.sh}) \tag{18}$$

$$D_e = \left(4 \,.\left[(\sqrt{3}. P_t^2/4) - (\pi . d_o^2/8)\right]\right) / \,(\pi \,.\, d_o/2) \tag{19}$$

$$Re_D = \frac{\rho_{ref} . v_{ref}\, D_e}{\mu_{ref}} = (\dot{m}_{ref} .\, D_e) / \,(A_{c.sh} \,.\, \mu_{ref}) \tag{20}$$

$$Nu_{sh} = \frac{h_{ref\,.} D_e}{k_{ref}} = 0.021 . Re^{0.55} . Pr^{1/3} . \left(\frac{\mu_{ref}}{\mu_{wall}}\right)^{0.14} \tag{21}$$

$$h_{ref\,.} = (Nu_{sh} \,.\, k_{ref})/D_e \tag{22}$$

Substitute the value of both $h_{a\,,} h_{ref}$ into Equation 8, to evaluate the overall heat transfer coefficient U, then last the step is calculating the active area of heat transfer from Equation 4, to find suitable design length. Now all design parameters become available to design the geometry.

$$A_{h.t} = \dot{Q}_t / \,(U . \Delta T_{lm}) \tag{23}$$

$$A_{h.t} = L_t . \pi . d_{t.i} . N_t \;\rightarrow L_t = A_{h.t} \,/\, (\pi . d_{t.i} . N_t) \tag{24}$$

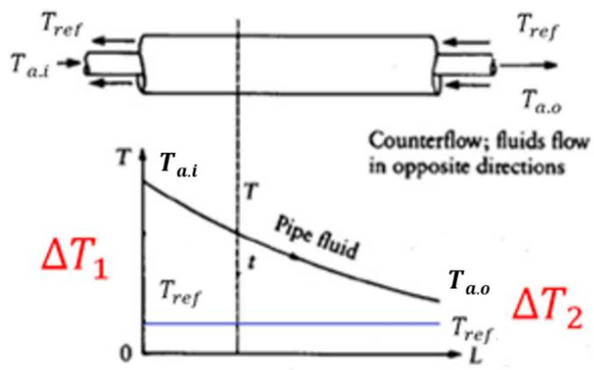


Figure 4. Evaporative heat exchanger MLTD.

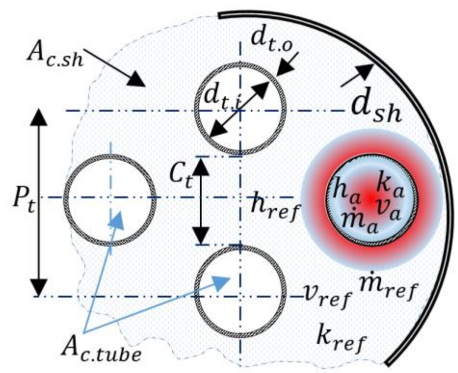


Figure 5. Tube triangular pitch layout.

ε-NTU pressure drop method equations

When there is insufficient information about fluid outlet temperature or pressure for both shell and tube side to calculate the log-mean temperature difference LMTD. The number of transfer units -NTU method used to calculate the rate of heat transfer in heat exchangers (especially countercurrent flow exchangers). For the shell domain where the coolant fluid is refrigerant, the pressure droop is zero due to latent heat face changeable substance expandable in isothermal and constant pressure (ΔP = zero) as $(T_{ref.in} = T_{ref.out})$ $(P_{ref.in} = P_{ref.out})$. Therefore, the tube pressure drop will be the dependent variable. Assuming minimum pressure drop as the geometry designed for minimum pressure loses to find suitable effective tube length.

Shell pressure drop

The pressure drop in the shell side is (zero), latent heat transfer face change coolant with constant pressure and temperature.

Tube side pressure drop

Friction factor for flow inside the tube from Equation. (13)

$$\Delta P = 4\left[\frac{f.L_t}{d_i} + 1\right] N_p.\frac{\rho_a \, . v_a^2}{2} \tag{25}$$

$$\varepsilon = 2\left[1 + C_r + (1 + {C_r}^2)^{0.5} \, \frac{1 + \exp(-NTU_1 \, . (1 + C_r^2)^{0.5})}{1 - \exp(-NTU_1 \, . (1 + C_r^2)^{0.5})}\right] \tag{26}$$

Or

$$\varepsilon = \frac{(\dot{m} \, . c_p)_{max}}{(\dot{m} \, . c_p)_{min}} \frac{T_{a.i} - T_{a.o}}{T_{a.i} - T_{ref}}$$

Capacity ratio

$$C_r = \frac{(\dot{m} \, . c_p)_{min}}{(\dot{m} \, . c_p)_{max}} \tag{27}$$

Heat transfer rate

$$q = \varepsilon \, (\dot{m} \, . c_p)_{min}. (T_{a.i} - T_{ref}) \tag{28}$$

$$NTU = \frac{U_o. \, A_o}{(\dot{m} \, . c_p)_{min}} \tag{29}$$

CFD approach

The present simulation ANSYS platform represents a powerful tool high suitability and accuracy, has efficient commercial computational fluid dynamics-CFD codes for estimating solution for thermal and hydraulic performance. ANSYS CFX, Fluent, Study-state thermal are a high-performance computational fluid dynamics CFD software tool that delivers reliable and accurate solutions quickly and robustly across a wide range of CFD and multi-physics applications [27]. Parametric studies conducted on IHE geometries fluid and solid sections to isolate and quantify the influence of individual geometric parameters. From the theoretical analysis results, an output design geometry is approached that can be adopted by varies vehicle for varies cooling capacity controlled by the coolant-refrigerant through an expansion valve which feeds the evaporative shell domain to reach lower temperature effect if desired.

Simulation parameter

In conventional IHE shell-and-tube type, the design scale is dependent of parameters of thermal capacity load or scale requirement. In this process the parameters are related to vehicle status, is it new vehicle concept design or available vehicle for modification and development? In vehicle modification, the space inside the engine area is controlling the IHE design scale for maximum space allowable available. Table 3, presenting variation predicting shell diameter – $D_{sh.i}$ scale allowed, selection depends on available space in engine area which controls the maximum $D_{sh.i}$ of IHE. The thermal load method presented in case of available space. The results present various tube length configurations depend on the selective case; the designer will be able to select an optimum qualified scale suitable for utilizing.

Approach design

The theoretical investigation of IHE and design c helped to understand the behaviour of IHE parameter relations to come out with a selected design geometry with specific dimension full-fled the cooling capacity required with optimized size reliable to be used in engine CAC system.

Figure 7The geometry scale dimension framework outcomes scale of IHE in both case of thermal load and pressure drop method introduced variable scale. Selecting a CFD geometry scale for computational study dependent in case of assuming maximum allowable space for $D_{sh.i}$ is 120 mm and selecting an average effective tube length of 150 mm was selected as shows in Table 1 and Figure 6 which, shows the IHE scale selection from parameter relationships of the geometry design refer to Table 3, selected for computational fluid dynamic performance test, assuming as qualified scale in selection between three of shell diameters of 80 mm, 100 mm, 120 mm.

Table 1. The selective dimension of geometry.

Shell $D_{sh.i}$ mm	Tube L mm	Tube d_i mm	Tube d_o mm	Tube layout	Tube pitch mm	Baffle No.	Baffle spacing	Airflow $\dot{m}_a$
120	150	7.53	9.53	Triangle	15	3	L/4	CFM

Parameter relationships of the geometry design are the IHE tube length – L and shell internal diameter scale $D_{sh.i}$, which control the number of tubes - Nt required for selected thermal load or pressure drop method.

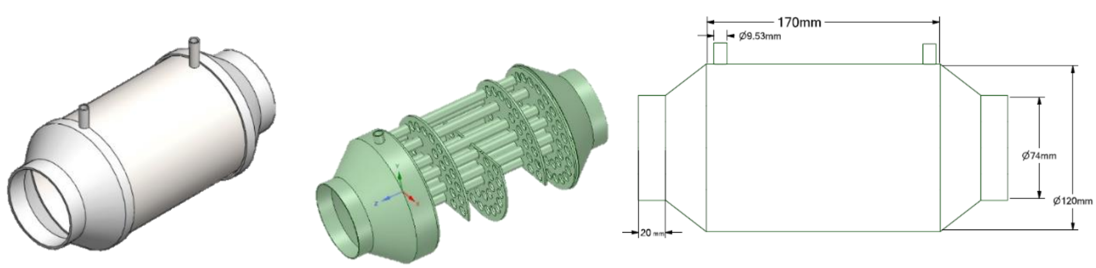


Figure 6. IHE geometry design.

RESULTS AND DISCUSSION

The theoretical and CFD study shows a significant thermal performance influence than the other designs of IHE presented in literature, which introduce better study range and performance for CAC influence engine operation as shown in Table 2, which presents the theoretical effect of air charge temperature on engine thermal performance and fuel consumption as presented by Yan et al.[5]; Moahamad [6], the engine performance increase with a decrease in ambient temperature. Flexibility in design method introduced a significant design control scale as in case of pressure drop, which introduced a multi-scale option for designer for selection compare with other IHE designs presented by Cuong et al. [21]; Richard et al. [22]; Wang and Ming [23]; M. Setiyo [24] ,which didn't presented any flexibility in their design scale control. Therefore, consideration to scale size of IHE becomes an important concern in vehicle designs as mentioned by Andreas and Marco [26]. The overall performance of the IHE depends on design scale control which controlled by space availability parameter in vehicle or pressure drop performance, which makes the design flexible to any size scale for the same thermal capacity required

Engine CAC performance case

Theoretical investigations on engine parameters, the thermal efficiency -η_{th} used to study the effect of CAC on engine behavior theoretically. Identifying the rate of work done by the combustion on the piston. Thermal efficiency (air-standard efficiency) of the Otto Cycle:

$$\eta_{th} = \frac{\dot{m}.c_v.(T_3 - T_2) - \dot{m}.c_v.(T_4 - T_1)}{\dot{m}.c_v.(T_3 - T_2)} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \qquad (30)$$

$$\eta_{th} = 1 - \frac{T_1}{T_2} = 1 - \left(\frac{V_2}{V_1}\right)^{k-1} = 1 - \left(\frac{1}{r}\right)^{k-1} \qquad (31)$$

The effective parameter effect on engine thermal performance is the temperatures, inlet temperature and combustion temperature [36]. Inlet temperature depends on ambient or IHE condition. Combustion temperature depend on burning combustion and heat released which vary with the amount of fuel/air ratio

$$\text{Compression ratio } r = V_1/V_2 \qquad (32)$$

A theoretical investigation study of CAC influence on engine thermal efficacy performance conducted through selective vary air temperatures nominated within the range of cold to hoot -20°C to 50°C, exploring a better understanding of temperature influence on engine performance [28 - 30].

Table 2, introduce the theoretical η_{th} results in selective variation air temperatures (-20 – 50°C) presenting the influence of temperature variation on engine thermal performance. The theoretical results show a development in engine thermal efficiency and better fuel consumption reduction in a constant engine speed of 2800 RPM, with fuel ratio 15:1, air mass flowrate is 0.055 kg/s, engine size is 1.496 liter. Theoretically, the results show a significant impact of CAC on engine performance.

Table 2. Influence of air temperature on engine performance.

Temp. °C	**ρ kg/m³**	**c_p N.s/m²**	**μ kg/m.s*10⁻⁶**	**ν m²/s *10⁻⁶**	**k w/m.c**	**Engine η_{th}**	**Fuel $\dot{m}_f$**
-20	1.394	1.005	1.630	1.169	0.0222	71	13.4
-15	1.368	1.006	1.655	1.210	0.0225	70.4	13.6
-10	1.341	1.006	1.680	1.252	0.0228	69.8	13.9
-5	1.317	1.006	1.704	1.295	0.0232	69.2	14.1
0	1.292	1.006	1.729	1.338	0.0236	68.7	14.4
5	1.269	1.006	1.754	1.382	0.0240	68.1	14.7
10	1.246	1.007	1.778	1.470	0.0243	67.5	14.9
15	1.225	1.007	1.800	1.470	0.0247	66.9	15.2
20	1.204	1.007	1.825	1.516	0.0250	66.4	15.5
25	1.184	1.007	1.872	1.562	0.0258	65.8	15.7
30	1.164	1.007	1.890	1.600	0.0262	65.2	16.0
35	1.145	1.007	1.918	1.650	0.0265	64.7	16.3
40	1.127	1.007	1.918	1.700	0.0266	64.1	16.5
45	1.109	1.007	1.941	1.750	0.0269	63.5	16.8
50	1.092	1.007	1.968	1.789	0.0273	62.9	17.1

The theoretical fuel consumption results in case of CAC. At Low air temperatures theoretically presented enhancement in fuel consumption.

Theoretical IHE study case

The theoretical investigation of the selected type of IHE presented the understanding of shell-and-tube heat exchanger variation with the effect of parameter relationships behaviours dependent on vehicle statues, which helps the designer for suitable design selection of IHE. The shell size becomes the main issue especially when the available space in engine housing control the design and not helpful for long tube length. The $D_{sh.i}$ α Nt, $Nt\ \alpha\ {}^{1}/_{L_t}$, $Nt\ \alpha\ d_{t.o}$, $D_{sh.i}$ α ${}^{1}/_{L_t}$ and $D_{sh.i}$ α ${}^{1}/_{\Delta P}$.

Table 3. Shell-and-tube parameters result for vary shell diameters

						Thermal method				**Pressure drop method**		
$D_{sh.i}$ m	$\dot{m}_a$ Kg/s	ΔT_{ML}	Nt	Re_D	Nu_t	h_a W/m².°C	U W/m².°C	A m²	Lt 1 m	Lt 2 m	Lt 3 m	Lt 4 M
0.08	0.055	37.75	35	8555	3.42	32.13	0.40	0.1	0.133	0.024	0.048	0.097
0.1	0.055	37.75	55	5475	2.16	27.6	0.35	0.1	0.09	0.052	0.10	0.20
0.12	0.055	37.75	79	3802	79	55.1	0.314	0.1	0.076	0.096	0.19	0.38

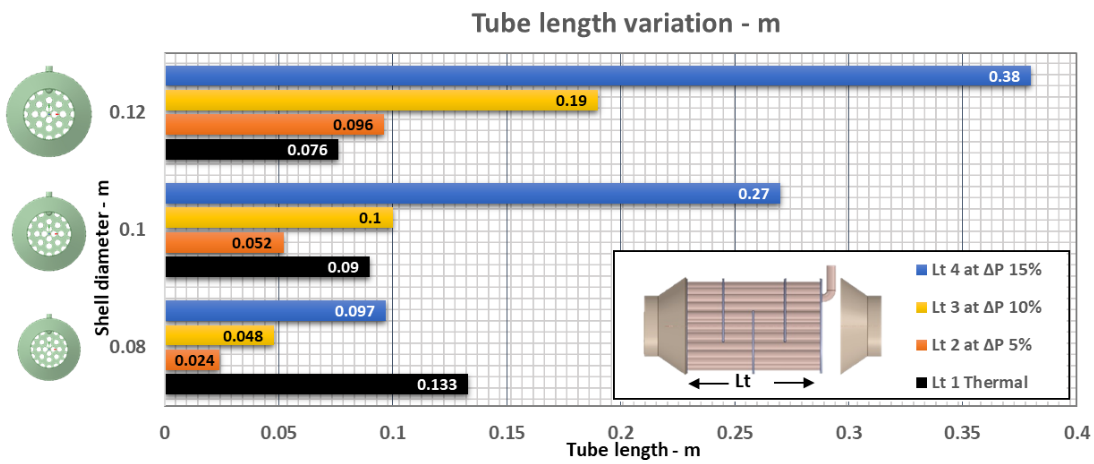


Figure 7. Variation IHE scale in a relation between $D_{sh.i}$ and tubes length L_t in (m).

Thus, as shown in Figure 7, the shell diameter is the controlled parameter which controls the amount of tube in IHE designs, $D_{sh.i}$ proportional to pressure drop in inverse relation. Tube length as same as relation with shell size for the same capacity. Short tube length reduces the friction flow over the tube surface minimizing the pressure drop but the surface area should be maintained for the same capacity.

Figure 8, presents the variable length of IHE in case of assuming a maximum shell diameter 120 mm as selection for the CFD study. The available space controlled the tube length parameter, L_2-L_4 tube length influenced by the parameter of pressure drop limitation, longer length presents friction between the tube surface and fluid flow across the tubes. Selecting maximum allowable space for design will reduce the tube length which helps to reduce the design cost and manufacturing process. In Figure 8, a selective geometry scaled design was selected within a suitable average scaled for computational analysis study case presented as CFD geometry with shell diameter of 120 mm as in Figure 6.

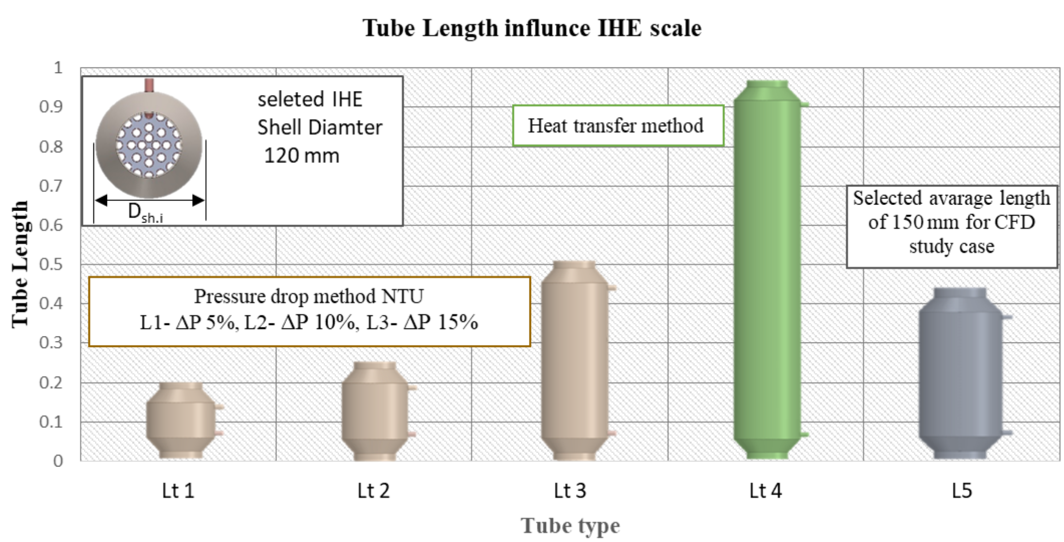
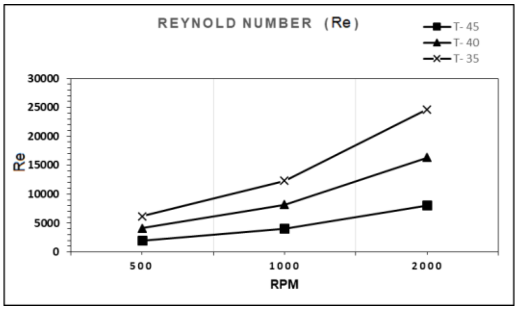
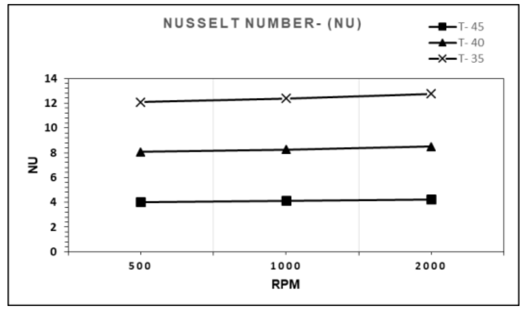


Figure 8. Vary IHE options scale for same $D_{sh.i}$.

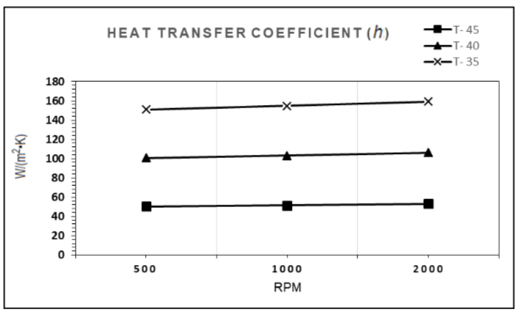
The theoretical observation of numerical analysis for selected IHE property results shows in Figure 9:



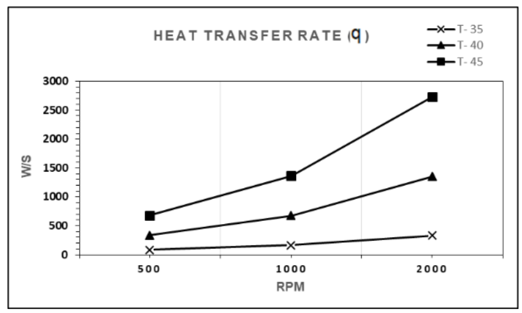
(a) Re Number



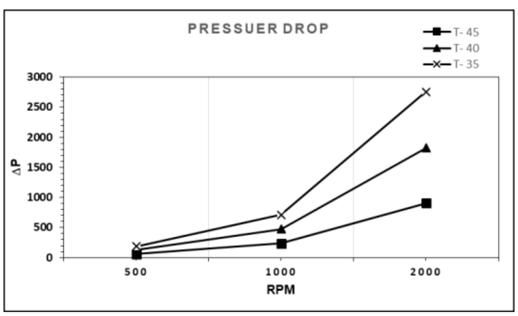
(b) Nu Number



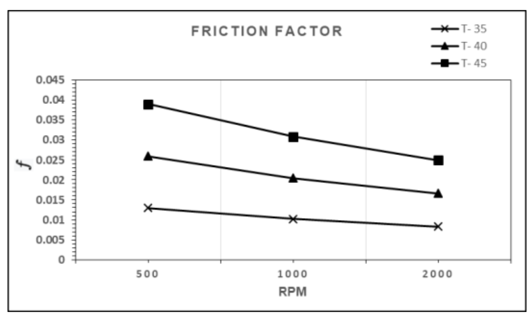
(c) Heat transfer coefficient



(d) Heat transfer rate



(e) ΔP- Pressure drop



(f) Friction factor

Figure 9. Theoretical analysis results of selected IHE design with varying temperatures: (a-b) are the air flow property through tubes, (c-d) presenting the thermal performance of IHE, (e-f) presenting air flow pressure drop and friction through tubes

CFD IHE case

ANSYS platform is used in design thermal analysis to identify in visual the scale parameters value and thermal behaver through the IHE. The new platforms of ANSYS provide advanced method system in elements meshing for a better option in creating required nods for the solution [37].

Figure 10, is the IHE geometry mesh of geometry shows the 5,399,148 elements with a number of meshing nodes of 1,468,658 nodes, presenting higher accuracy in solution.

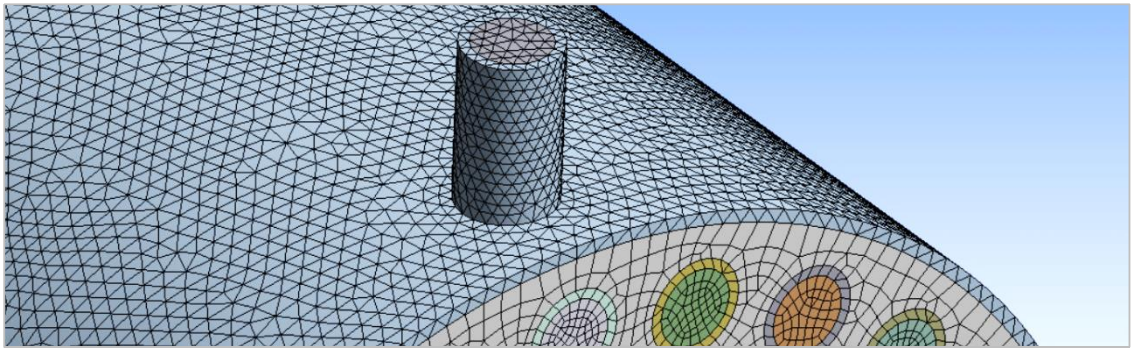


Figure 10.Geometry meshing performance.

the analysis shows the capability of the geometry for load variation in cooling effect by the refrigerant [38], the pressure drops value could be ignored as the air flow rate is very high proportional to engine RPM.

The design can be adopted by variation engine size and capacity for CAC influence. Refer to Figure 9, for selected shell diameter $D_{sh.i}$ of 120 mm, the air temperature results show reduction from 45^{o}C to 10^{o}C in same boundary conditions, the reduction reached lower temperatures with reduction of engine RPM, while leading to a reduction in airflow velocity leading to rising in time of contact surface between the air and tubes surfaces. Figure 11, shows the IHE cross section with refrigerant cooling and air flow domain through tubes, the tubes length is dependent of pressure drop control.

Figure 12-14, shows the heat transfer distribution analysis through the IHE tube calculated by CFD application introducing an effective thermal cooling performance by the refrigerant. Higher RPM reduced the time of contact between the fluid and cooling surface due to flow velocity causing a reduction in cooling effect, temperature deference becomes lower. That's why for the higher cooling effect the length of the tube should be longer but that will cause more pressure drop on slower RPM, or rise the contact surface area of the cooling surface for the same length [39].

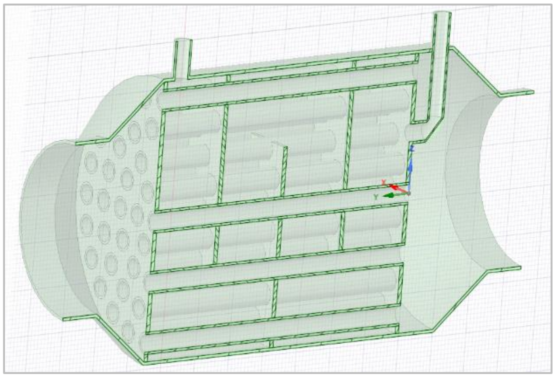


Figure 11. Shell portion.

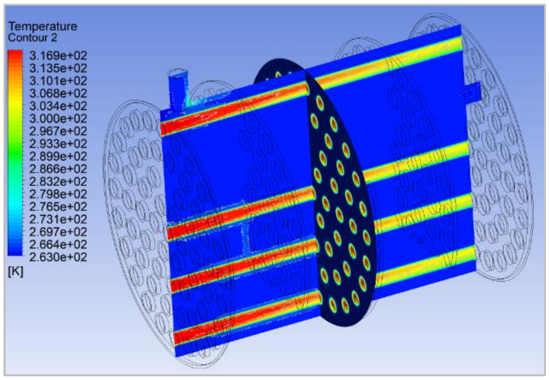


Figure 12. Shell portion heat transfer flow cross section.

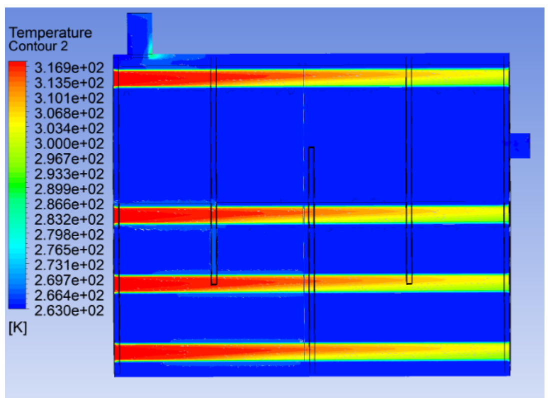


Figure 13. Shell portion heat transfer streams.

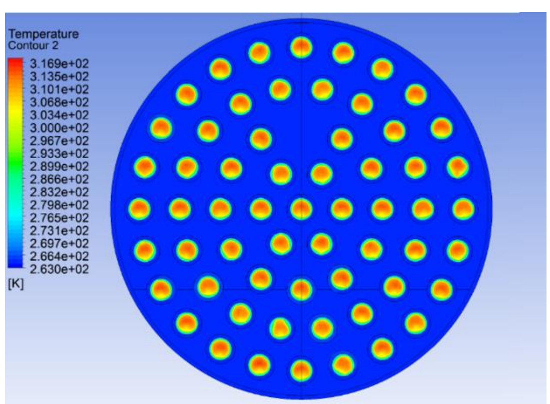


Figure 14. Heat transfer stream through tubes.

The investigation study shows a pressure drop influence through IHE flow compare with initial engine airflow inlet pressure, the temperature reduction influenced the air density property influencing air volumetric size at constant mass air flow and constant combustion volume to be reduced, leading to change in air molecular pressure, as the temperature is directly proportional to volume ($T \propto V$, $T \propto P$ and $P.V = n.R.T$) [40].

The CFD simulation in case of thermal study state conditions**Error! Reference source not found.Error! Reference source not found.**, Figure 15, shows the distribution of heat transfer energy between the tubes and shell domain, the cooling effect is higher in the refrigerants supply line, gradually reduced when reaching towered the air supply line due to higher ambient temperature. The refrigerant converts into gas due to evaporation absorbing the heat from the tubes wall, the heat transfer from the hot air into the refrigerant through the tube wall. The cross-section area of the bunch tubes helps to add more heat transfer area [41]. The amount of cooling capacity will depend on the surface area of heat transfer, which is dependent of IHE tube numbers and length.

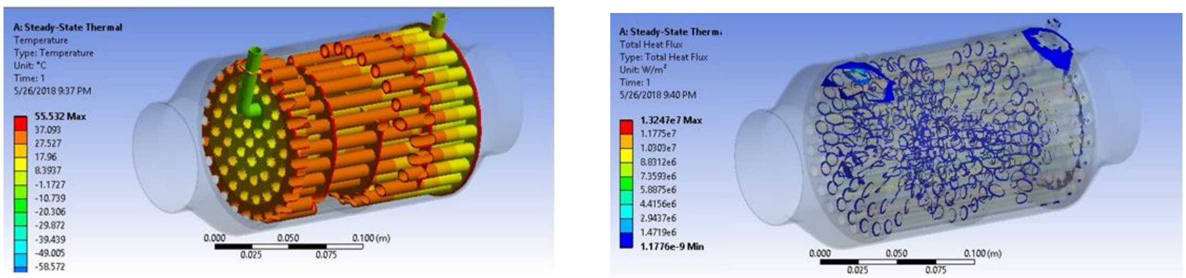
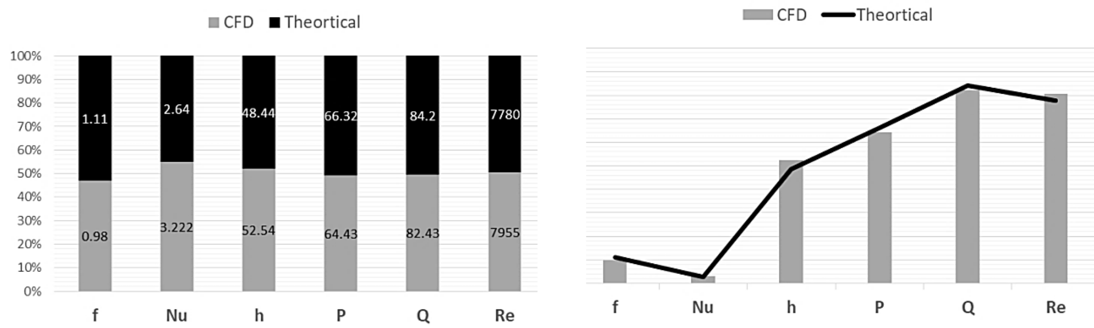


Figure 15. A study state thermal analysis showing the thermal heat distribution through IHE.

Theoretical verification approach

Both boundary condition of IHE theoretical and CFD analysis for selected boundary conditions of inlet and outlet air with the engine capacity and speed considered in the analysis used to compare the results. Figure 6, is the selected geometry dimension applied in CFD analysis with the same boundary conditions of air supply temperatures and flow rates same as used in theoretical solutions. The tube outlet and inlet temperatures utilized at different conditions. Figure 16, representing variable parameters results in IHE both theoretical and computational comparison in accuracy of results. The graph correlation between CFD and theoretical gap return to the quality of CFD platform equation calculation as the CFD platform use higher order equations, which gave an accurate result close to real life conditions that certify the reality of the ANSYS ability in simulations. The variation in value solved by the CFD solution to general mathematical equation solution return to the quality of equation order. The CFD recommended for better accuracy validating in future geometry design due to its boundary condition accuracy.



(a) Verifications analysis (b) verification accuracy

Figure 16. Geometry Verification correlation: (a) - CFD and theoretical analysis value with percentage evaluation. (b) – results verification correlation CFD and theoretical

CONCLUSIONS

The selected shell-and-tube heat exchanger geometry utilized for use in engine charge air cooler- (CAC) intercooler, based on framework process method and design consideration, which used for determination of exact optimum value of the IHE geometry scale, successfully presented a satisfy capability in design required condition in both case of space availability or pressure drop allowable, presenting time and design accurate enhancement.

The numerical and CFD simulation investigation analysis of selected model as in Table 9, shows a significant thermal capability influence on air thermal property compare with other conventional IHE utilized in the market. Evaporative coolant medium type presented a significant method for better cooling capacity, as a result, Table 2, shows significant influence on engine thermal performance and fuel consumption enhancement due to lower temperature cooling capability. The design consideration limitation presented in technical expertise required for manufacturing and Installation of the IHE on the engine. The flexibility of use as air cooler or liquid cooler with the ability of reversibility of the refrigeration heat pump in use of cycle reversing valve for heating effect, this option qualifies the design for utilizing in all engine types in both charge air pre-heating or cooling system. The evaporative IHE can be utilized in systems which require higher cooling capacity with system size consideration as the selected IHE type presented a smaller scale than other conventional IHE available in the market.

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REFERENCES

[1] Minet L, Liu R, Valois MF, Xu J, Weichenthal S, Hatzopoulou M. Development and comparison of air pollution exposure surfaces derived from on-road mobile monitoring and short-term stationary sidewalk measurements. Environmental Science & Technology. 2018; 52(6):3512-3519.

[2] Hesselgreaves JE, Law R, Reay D. Compact heat exchangers: Selection, design and operation. 2nd ed. Butterworth-Heinemann: Elsevier Science; 2016.

[3] Ranganayakulu C, Seetharamu KN. (2018). Compact heat exchangers: Analysis, design and optimization using FEM and CFD approach. New York: John Wiley & Sons; 2018.

[4] Huang Y, Hong G, Huang R. Investigation to charge cooling effect and combustion characteristics of ethanol direct injection in a gasoline port injection engine. Applied Energy 2015; 160: 244-254.

[5] Chang Y, Mendrea B, Sterniak J, Bohac SV. Effect of ambient temperature and humidity on combustion and emissions of a spark-assisted compression ignition engine. Journal of Engineering for Gas Turbines and Power 2017; 139(5): 51501–51507.

[6] Aziz MFA. The effect of ambient temperature to the performance of internal combustion engine. Dissertation Universiti Tun Hussein Onn Malaysia; 2015.

[7] Laurinaitis K, Slavinskas S. Influence of intake air temperature and exhaust gas recirculation on HCCI combustion process using bioethanol. In: 15th Internal Scientific Conference on Engineering for Rural Development, Latvia University of Agriculture, Jelgava, Latvia; 25-27 May 2016, pp.536–541.

[8] Irimescu A, Merola SS, Tornatore C, Valentino G. Effect of coolant temperature on air: Fuel mixture formation and combustion in an optical direct injection spark ignition engine fueled with gasoline and butanol. Journal of the Energy Institute 2017; 90(3): 452–465.

[9] Birtok-Băneasă C, Raţiu S, Hepuţ T. Influence of intake air temperature on internal combustion engine operation. In: IOP Conference Series: Materials Science and Engineering, Vol. 163(1); p.012039, IOP Publishing; 2017.

[10] Magar YV, Sundar D. Optimization of air intake system and exhaust system for better performance of turbocharged gasoline engine. SAE Technical Paper; 2018.

[11] Novella R, Dolz V, Martín J, Royo-Pascual L. Thermodynamic analysis of an absorption refrigeration system used to cool down the intake air in an internal combustion engine. Applied Thermal Engineering 2017; 111: 257–270.

[12] Dzida M, Prusakiewicz P. The effect of temperature and pressure on the physicochemical properties of petroleum diesel oil and biodiesel fuel. Fuel 2008; 87(10–11): 1941–1948.

[13] Naser L, Ilir D, Shpetim L. Modelling and simulation of the turbocharged diesel engine with intercooler. IFAC-Papers OnLine 2016; 49(29): 237–242.

[14] Andersson P, Eriksson L. Mean-value observer for a turbocharged SI-engine. IFAC Proceedings Volumes 2004; 37(22): pp.131–136.

[15] Amir K. Effect of ambient temperature and oxygen concentration on ignition and combustion process of diesel spray. Asian Journal of Scientific Research 2013; 6(3): 434-444.

[16] Andsaler AR, Khalid A, Jaat N, Sukarman MI. Effects of ambient density on flow characteristics of biodiesel spray injection using computational fluid dynamics. ARPN Journal of Engineering and Applied Sciences 2016; 11(8): 5499–5505.
[17] Patil C, Varade S, Wadkar S. A review of engine downsizing and its effects. International Journal of Current Engineering and Technology 2017; 7(7): 319-324.
[18] Pawar N. Thermal design and development of intercooler. In: International Conference on Global Trends in Engineering, Technology and Management-ICGTETM 2016: 9–17.
[19] Ni P, Wang X, Wei S. Effects of intake air temperature on SI engine emissions during a cold start. International Journal of Sustainable Energy 2014; 33(2): 243–250.
[20] Patil V, Malipatil AS. CFD analysis of intercooler with sinewave fins. International Journal of Engineering and Techniques 2017; 3(6): 764–765.
[21] Quoc CD, Dinh TL, Trong TD. Research on heat exchanger between water with air in an intercooler based on CFD. In: 4th International Conference on Green Technology and Sustainable Development (GTSD), IEEE, pp. 374–378, 2018.
[22] Brouillard E, Burns B, Khan N, Zalaket J. The design and manufacturing of an intercooler assembly with R-134a integration. Boston: Prestige Worldwide, Wentworth Institute of Technology; 2011.
[23] Jia-Wei W, Hsueh M. The analysis of engine intake air cooling device by using thermoelectric module. In: Juang J, Huang YC. (Eds.). Intelligent technologies and engineering systems. Lecture notes in electrical engineering, vol 234. New York, NY: Springer; 2013.
[24] Setiyo M, Syaka DRB, Waluyo B, Hamidi N, Kiono BFT. Cooling effect potential from liquefied petroleum gas flow in the fuel line of vehicle. International Journal of Automotive & Mechanical Engineering 2017; 14(4): 4704-4714.
[25] Quinones LGO, Viana LFA, Ochoa GEV. Thermal design and rating of a shell and tube heat exchanger using a matlab® GUI. Indian Journal of Science and Technology 2017; 10(25): 1–9.
[26] Kaechele A, Chiodi M, Bargende M. Virtual full engine development: 3D-CFD simulations of turbocharged engines under transient load conditions. SAE International Journal of Engines 2018; 11(6): 697-713.
[27] ANSYS. ANSYS CFX. Retrieved from https://www.ansys.com/products/fluids/ansys-cfx; 5 December, 2018.
[28] Galindo J, Climent H, Varnier O, Patil C. Effect of boosting system architecture and thermomechanical limits on diesel engine performance: Part 1 - Steady-state operation. International Journal of Engine Research 2018; 19(8): 854-872.
[29] Hu T, Wei Y, Liu S, Zhou L. Improvement of spark-ignition (SI) engine combustion and emission during cold start, fueled with methanol/gasoline blends. Energy & Fuels. 2007; 21(1): 171-175.
[30] Pan W, Yao C, Han G, Wei H, Wang Q. The impact of intake air temperature on performance and exhaust emissions of a diesel methanol dual fuel engine. Fuel 2015; 162: 101-110.
[31] Tacconi J, Visser W, MacNeill R, Verstraete D. Development of a multi-objective optimization tool for intercooled/recuperated turboprop engines for minimum SFC and engine weight. In: 2018 Joint Propulsion Conference, 9-11 July, 2018.
[32] Sundaresan R. Multiphase simulation of automotive hvac evaporator using r134a and

r1234yf refrigerants. International Journal of Automotive and Mechanical Engineering 2017; 8(2): 263–270.
[33] Zhou G, Li H, Liu E, Li B, Yan Y, Chen T, Chen X. Experimental study on combined defrosting performance of heat pump air conditioning system for pure electric vehicle in low temperature. Applied Thermal Engineering 2017; 116: 677–684.
[34] Vittorini D, Di M, Di D, Cipollone R. Charge air subcooling in a diesel engine via refrigeration unit: Ubcooling in a diesel engine via refrige. Energy Procedia 2018; l48: 822–829.
[35] Cipollone R, Battista DD, Vittorini D. Experimental assessment of engine charge air cooling by a refrigeration unit. Energy Procedia 2017; 126: 1067–1074.
[36] Akasyah MK, Mamat R, Abdullah A, Aziz A, Yassin HM. Effect of ambient temperature on diesel-engine combustion characteristics operating with alcohol fuel. International Journal of Automotive & Mechanical Engineering 2015; 11: 2374-2382.
[37] ANSYS. ANSYS meshing. [Online]. Retrieved from https://www.ansys.com/products/platform/ansys-meshing; 5 December, 2018.
[38] Chng MH, Chin WM, Tang SH. Analysis on the refrigerant (R32) flow maldistribution of microchannel heat exchanger under superheat and sub-cool. International Journal of Automotive and Mechanical Engineering 2017; 14(2): 4140–4157.
[39] Azman NA, Samsuri S, Jusoh M. Effect of freezing time and shaking speed on the performance of progressive freeze concentration via vertical finned crystallizer. International Journal of Automotive and Mechanical Engineering 2018; 15(2): 5356-5366.
[40] Tenny KM, Cooper JS. Ideal gas behavior. [Updated 2019 Jan 19]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2019.
[41] Sheikholeslami M, Gorji-Bandpy M, Ganji DD. Review of heat transfer enhancement methods: Focus on passive methods using swirl flow devices. Renewable and Sustainable Energy Reviews 2015;1(49): 444–469.