The development of an aftermarket intercooler spray for turbocharged vehicles using ethylene glycol and hyaluronic acid

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Abstract. Intercooler is used in motor vehicles to cool the air compressed by a turbocharger. Engine heat and weather condition commonly influence the efficiency of the intercooler, and this in turn affects the overall engine’s power output. The objective of this study was to design and develop an autonomous cooling system for top-mounted intercooler. The system was powered by Arduino Uno microcontroller that gathers data from the temperature sensor and triggers the spraying mechanism automatically when required. Besides, the system could also be operated manually via a switch by the user. The experimental results showed that the efficiency of the normal intercooler without the spray cooling unit was improved from 56.52% to 90.72% and the minimum possible efficiency with the spray cooling unit was 32.38% more efficient. Upon using ethylene glycol as the spray medium, the system achieved 90.70% efficiency. Even so, hyaluronic acid had the most effective heat absorbing capacity as its efficiency was 90.72%. This proved that the cooling process through spray cooling unit had a vast improvement on the efficiency of the intercooling system. Generally, for all three independent variables, temperature drop increases with the increasing amount of pressure created by the additional pumps, hence, efficiency of the system increases. However, for hyaluronic acid, the efficiency is also dependent on its texture and viscosity. This newly designed portable plug-and-play intercooler spray unit would be beneficial to increase the performance of the intercooler by improving the heat exchange capacity of the unit. For future studies, other types of spray cooling medium or combinations of several cooling mediums could be tested.

1. Introduction
In the automotive industry, turbochargers are used in internal combustion engine for forced induction [1, 2]. Turbochargers consists of two impellers attached to the same shaft spinning around together. One of these impellers called turbine sits on the exhaust steam from the cylinder, whilst, the second impeller – known as compressor is located inside the car’s intake, forcing air into the engine’s combustion chamber. In the 1970s many experimental applications and research were done, one of which was when an air to air intercooler was attached to a 164 horsepower (hp) tractor and it was observed that the engine power output increased with no side effects [3, 4]. In 1987, Thompson et al suggested that more than 20,000 hp and 30% reduction in fuel consumption were attained by regenerator and intercooler usage in marine engines [5].
In the late 1980s, majority of the studies focused on diesel engine,(7,419),(994,995) whilst, in the 1990s there were high portion of both theoretical and experimental studies on force induction with the use of intercooling on diesel and spark ignition engines [6]. The studies mainly suggested that forced induction increases the power output while maintaining low fuel consumption. In the late 1990s, there were various experimental studies on intercooling effects on engine behaviour. Through studies done by Uzun, it was reported that the fuel consumption of a diesel engine decreased by 3%-13% with the use of intercooler [7]. Bilen developed a software predicting performance of an intercooler to its dimension and vice versa by the use of effectiveness transfer unit method [8]. The capacity of gases via exhaust was improved by 15.78%, the fuel consumption reduced by 9.5% and the power output increased by 3%. Exhaust emission proportion through the use of intercooler was studied by Ozulku with European Steady State Test cycle MOD 13 and it showed a similar result for fuel consumption and power output. However, the particle emission dropped from 20 to 50%, NO emission dropped from 4 to 24% and hydrocarbon emission also dropped from 20 to 24% [9]. Finally, from various case studies done recently on homogeneous charge compression ignition engine, the fuel consumption decreased by 50% and had a power output of 146 kW through forced induction via intercooling which passed Euro 6 emission regulations [10].

However, the strength of force induction system has unfortunately its own demise as well. As noted by the ideal gas law, air pressure is directly proportional to its temperature [11]. Henceforth, force induction would result in the increment of air temperature. It should be noted that air at higher temperature is in fact less dense, hence, does not provide the best form of combustion. On top of this the temperature in the engine bay and also the temperature outdoor affect the temperature of the air that enters the air intake. Therefore, the hot air coming from the compressor is passed through a heat exchanger known as an intercooler [12]. With respect the intercooler, at best, this heat (from various sources) is transferred to the surrounding by convection with the help of intercooler fins, so that the air leaving the intercooler is colder and denser, making more oxygen molecules per unit volume for thorough combustion [13]. One of the methods in overcoming the efficiency of the intercooler with respect to air temperature is by utilizing a spray cooling.

Spray cooling is the process of spraying small droplets on heated surfaces in order to increase the effective heat transfer to surrounding when cooling media changes phase [14]. Spray cooling is used in areas such as cooling of hot surfaces in hot strip mill, fire protection, cooling hot gases, cooling high performance electronic devices and dermatological operations in the medical field. Sprinkler system in a fire protection system works by the general law of spray cooling. The discharged water through the nozzle gets atomized into the ambient where tiny droplets are in charge to control or stop the fire. The small droplets spread over a large surface area over the unsaturated ambient air promotes evaporation. As high latent heat is absorbed by the water droplets in the evaporation process, the heat released at the fire can be controlled and prevented from spreading. Moreover, spray cooling is vastly used in metal production and processing industry for high temperatures steel strip casting where temperatures reach over 1800K and the optimization of the microstructure after the hot rolling process. In these processes a gas jet carrying water is sprayed onto the hot surface which needs to be cooled. It can be seen Spray cooling has one of the highest heat flux and heat transfer coefficient. On top of this, Spray cooling is vastly used in various different fields as it uses few components and less complex thus, making it less bulky, more reliable and cheaper to run. Furthermore, cryogenic spray cooling in the medical field is used for precooling of human skin during laser treatment for hair and birthmark removal. This is done to avoid permanent thermal damage on the skin from large temperature differences between the targeted vessels and epidermis. A cryogenic spray is used to spray on the skin surface for a short time interval before the laser treatment is proceeded. In the electric field, spray cooling has the greatest attention because of its ability to remove high heat flux (1200 W/cm²) while keeping the device temperature below 100 °C with spatial and temporal variations below 10 °C [15]. Spray cooling is being used in high performance computers such as CRAY X-1 and promising results are being shown for the management of heat through high power insulated gate bipolar transistors [16], microwave source components [17] and laser diode laser arrays [18]. The present study is aimed to overcome this
issue by promoting heat exchange through spray cooling with an automatic spraying mechanism spraying a certain liquid at a given concentration and pressure to promote evaporative cooling.

2. Methodology

2.1. Identifying critical parameters involved

In identifying the list of critical parameters i.e. controls and variables involved in designing portable plug-and-play intercooler spray unit for automobile; intensive literature review was conducted. The literatures were crucial in providing the necessary information in designing the portable plug-and-play intercooler spray unit for automobile. Through finding out the parameters involved in the whole system, the scope of the project and possible future studies were thought through. The parameters which were set as controlled, independent, and dependent variables for this project are shown in table 1.

| Controlled Variables | Independent Variables | Dependent Variable |
|----------------------|-----------------------|--------------------|
| Inlet Temperature    | Type of Spray Medium  | Outlet Temperature |
| Ambient Temperature  | Concentration          |                    |
| Ambient Humidity     | Pump Pressure          |                    |
| Speed of Air         |                       |                    |
| Nozzle Type          |                       |                    |
| Nozzle Diameter      |                       |                    |
| Pipe Diameter        |                       |                    |
| Time of Spray        |                       |                    |

The outlet temperatures were measured at the intercooler after the use of spraying mechanism with the change of each independent variable. The outlet temperature was chosen as it is the most important parameter in the intercooler/heat exchanger and it is directly linked to the efficiency of the whole unit. The dependent variable, outlet temperature, was measured by a feedback system spraying a fluid automatically for the set spray time just when the temperature reaches an assigned value. Upon the completion of spray cooling, the lowest temperature at the intercooler outlet was measured and temperature drop before and after spraying at the intercooler outlet was calculated. The lowest temperature was taken over the temperature after a certain period of time as this project mainly focused on the maximum effects of the spraying mechanism and not the rate at which the cooling process happened. By using outlet temperature of the intercooler as the dependent variable to calculate the temperature drop, the efficiencies of the Intercooler before and after the spray cooling process were found.

In the experiment, two types of liquid (independent variables) were used: ethylene glycol and hyaluronic acid. For the hyaluronic acid and the glycol solution, different concentration of the medium (mixed with water) were tested. The goal was to determine spray medium that gives the highest decrement of outlet temperature i.e. the best cooling effects and the overall highest efficiency of the system developed.
2.2. Layout of the system
The system works by sensing the temperature at the intercooler exit using the temperature sensor. When the temperature reaches above a certain value, the relay turns on to start the pump and spray water onto the intercooler lowering the temperature. The temperature was analysed by the sensing element throughout, and if the temperature does not drop, the loop continues and sprays until the temperature reaches below the designated value. The independent variables were varied, and the dependent variable was measured to study the effects of these parameters on spray cooling. Schematic diagram of the system is depicted in figure 1.

![Schematic diagram of the system.](image)

**Figure 1.** Schematic diagram of the system.

In the feedback system, as the exit temperature reaches above a certain value, the micro controller detects the increase in temperature by the data sent by AM2302 sensor. The microcontroller sends a small current to the relay, turning on the pump and spraying fluid stored in the tank. Through having this feedback system, during testing there was less human error as the Controller controlled the spray mechanism when the set temperature was reached, and this was preferred than waiting for a temperature to reach and spray manually. However, a switch was used for manual use so that the spray can be used manually in case of any malfunction or during fluid change. The whole system was powered by a 12V DC supply, which is similar to that in motor vehicles. Peak inlet and outlet temperatures were measured to find the efficiency of the intercooler without the spray cooling mechanism for comparison with the efficiency of the spray cooling unit. On top of this, the outlet temperature was set as the benchmark temperature to observe the improvement on the system as opposed to standalone unit. Table 2 shows the measured controlled variables.

| Ambient Temp. | Ambient Humidity | Peak Inlet Temp. | Peak Outlet Temp. without spraying (Benchmark Temp.) |
|---------------|-----------------|-----------------|-----------------------------------------------------|
| 24.5°C        | 24.70%          | 151°C           | 79.5°C                                               |

Table 2. Measured controlled variables.
The collected data for the dependent variable, outlet temperature and calculation was done to obtain the efficiency for comparison with the efficiency of the intercooler without the intercooler spray unit.

\[
\text{Temperature Drop} = \text{Inlet Temperature} - \text{Outlet Temperature} \tag{1}
\]

\[
\text{Efficiency} = \frac{(\text{Inlet Temperature} - \text{Outlet Temperature})}{(\text{Inlet Temperature} - \text{Ambient Temperature})} \times 100
\]

\[
= \frac{\text{Temperature Drop}}{(\text{Inlet Temperature} - \text{Ambient Temperature})} \times 100 \tag{2}
\]

Using equation (2) the efficiency of the intercooler without the spray unit was calculated to be 56.52%.

3. Results and discussion

Table 3 shows experimental results for Ethylene Glycol. Based on the results obtained, it was observed that all the three (3) independent variables follow a trend, which altered the dependent variable (Outlet temperature) in different ways. The amount of variations of the outlet temperature affected the temperature drop, and this influenced the variation of efficiencies of the system. The overall data collected could have uncertainties as temperature readings were recorded using both sensor and mercury thermometer. There could have been instrumental errors from the readings obtained through the Mercury thermometer; however, the error would be very small, approximately of 0.1 °C.

Table 3. Experimental results for ethylene glycol.

| Pressure | Concentration | Inlet Temperature | Outlet Temperature | Temperature Drop | Average Temperature Drop | Efficiency |
|----------|---------------|-------------------|--------------------|------------------|--------------------------|------------|
| 1        | 20%           | 151               | 38.5               | 112.5            | 112.60                   | 89.01      |
|          | 151           | 38.7               | 112.3             | 113              |                         |            |
|          | 151           | 38                   | 113                | 39.6          | 111.4                   |            |
|          | 151           | 40.1               | 110.9           | 41.3          | 109.7                   | 87.72      |
|          | 151           | 40.4               | 110.6            | 41.6          | 109.4                   |            |
|          | 151           | 40.8               | 110.2            |                |                         |            |
|          | 60%           | 151               | 41.3               | 109.7       | 109.77                   | 86.77      |
|          | 151           | 41.6               | 109.4            |                |                         |            |
| 2        | 20%           | 151               | 37.2               | 113.8         | 113.47                   | 89.70      |
|          | 151           | 37.5               | 113.5           | 37.9          | 113.1                   |            |
|          | 151           | 37.9               | 113.1            | 39.5          | 111.5                   |            |
|          | 151           | 39.5               | 111.5            |                |                         | 88.17      |
|          | 151           | 39.4               | 111.6            | 40.1          | 110.9                   |            |
|          | 151           | 40.1               | 110.9            |                |                         |            |
|          | 60%           | 151               | 40.5               | 110.5         | 110.60                   | 87.43      |
|          | 151           | 40.6               | 110.4            |                |                         |            |
| 3        | 20%           | 151               | 36.5               | 114.5         | 114.73                   | 90.70      |
|          | 151           | 36.2               | 114.8            | 36.1          | 114.9                   |            |
|          | 151           | 36.1               | 114.9            | 38.6          | 112.4                   |            |
|          | 151           | 38.6               | 112.4            |                |                         |            |
|          | 40%           | 151               | 38.5               | 112.5         | 112.60                   | 89.01      |
|          | 151           | 38.1               | 112.9            | 38.1          | 112.9                   |            |
|          | 151           | 39.8               | 111.2            |                |                         |            |
|          | 60%           | 151               | 39.7               | 111.3         | 111.17                   | 87.88      |
|          | 151           | 40                   | 111                |                |                         |            |
Ethyl Glycol solutions followed a general trend where the temperature drop decreased as the concentration increased. However, as the pressure increased, the temperature drop started to increase. In the case of Ethyl Glycol peak efficiency of 90.70% was achieved where the pressure generated was the highest for the lowest concentration of 20% of the spray medium. With the same pressure for the 40% concentrated spray medium the efficiency was 89.01%, followed by 87.88% for the 60% diluted solution. Furthermore, the lowest efficiency with this spray medium was 86.77% with a 60% diluted solution with the lowest pressure set up. It was observed that the concentration is inversely proportional to the temperature drop and the temperature drop increases slightly as the pump pressure increases.

This trend was studied in the literature review, where it was stated that with increasing amount of Glycol in a solution the thermal absorbing capacity of the fluid. As the concentration of glycol increased, the specific heat capacity of the glycol and water mixture reduces, therefore the least optimum amount of glycol was recommended. However, as the pressure was increased, the nozzle sprayed the solution in form of tiny droplets over a wide area which efficiently increased the heat absorbing capacity of the diluted solutions.

**Table 4.** Experimental results for Hyaluronic acid.

| Number of Pumps | Concentration | Inlet Temperature | Outlet Temperature | Temperature Drop | Average Temperature Drop | Efficiency |
|-----------------|---------------|-------------------|--------------------|------------------|-------------------------|------------|
| 1               | 20%           | 151               | 39.7               | 111.3            | 111.57                  | 88.19      |
|                 | 40%           | 151               | 39.4               | 111.6            |                         |            |
|                 |               | 151               | 39.2               | 111.8            |                         |            |
|                 |               | 151               | 40.2               | 110.8            |                         |            |
|                 | 60%           | 151               | 40.1               | 110.9            | 110.67                  | 87.48      |
|                 |               | 151               | 40.7               | 110.3            |                         |            |
|                 |               | 151               | 41.6               | 109.4            |                         |            |
|                 |               | 151               | 41.8               | 109.2            | 109.40                  | 86.48      |
|                 |               | 151               | 41.4               | 109.6            |                         |            |
|                 |               | 151               | 38.1               | 112.9            |                         |            |
|                 | 20%           | 151               | 37.9               | 113.1            | 113.27                  | 89.54      |
|                 | 40%           | 151               | 37.2               | 113.8            |                         |            |
|                 |               | 151               | 39.7               | 111.3            |                         |            |
|                 | 60%           | 151               | 39.2               | 111.8            | 111.73                  | 88.33      |
|                 |               | 151               | 38.9               | 112.1            |                         |            |
|                 |               | 151               | 40.5               | 110.5            |                         |            |
|                 |               | 151               | 40.7               | 110.3            | 110.47                  | 87.33      |
|                 |               | 151               | 40.4               | 110.6            |                         |            |
|                 |               | 151               | 36                 | 115              |                         |            |
|                 | 20%           | 151               | 36.5               | 114.5            | 114.77                  | 90.72      |
|                 |               | 151               | 36.2               | 114.8            |                         |            |
|                 |               | 151               | 38.1               | 112.9            |                         |            |
|                 | 40%           | 151               | 37.8               | 113.2            | 113.17                  | 89.46      |
|                 |               | 151               | 37.6               | 113.4            |                         |            |
|                 |               | 151               | 40.1               | 110.9            |                         |            |
|                 | 60%           | 151               | 39.8               | 111.2            | 111.20                  | 87.91      |
|                 |               | 151               | 39.5               | 111.5            |                         |            |

Additionally, hyaluronic acid had the most effective heat absorbing capacity as its efficiency was 90.72%, as depicted in table 4. The hyaluronic acid followed a similar pattern to glycol. The reason behind this was because of high texture and high viscosity of the hyaluronic acid. As the concentration of hyaluronic acid increased, the mixture became thicker and viscous which made the temperature
drop fall. As the hyaluronic acid’s proportion increased and the pressure is reduced, the thick coarser liquid droplets started to form a gel coating before evaporating. Thus, this hindered the cooling process through evaporation as molecules are trapped from evaporating. The lowest efficiency recorded was 86.48%, which was also among the lowest efficiencies resulted from the thick layer formed with high percentages of hyaluronic acid. However, the use of higher pressure and less percentage of hyaluronic acid, the less viscous spray medium was sprayed over a wide area forming of blanket, covering a large surface area of small droplets that aided the cooling process through absorbing extra moisture from the surrounding and going through evaporative cooling. In the evaporative cooling, the molecules been evaporated after absorbing energy from the hot surface.

4. Conclusion
The present study designed, tested, and optimized aftermarket intercooler cooling spray unit. The independent variables, type and concentration of spray medium, and the pressure that should be generated to have an optimized prototype with good efficiency were studied and utilized for usage. It was found that the most efficient spray medium for spray cooling process was 20% Hyaluronic acid with water, followed by 20% Ethylene glycol solution. The efficiency of the normal intercooler without the spray cooling unit was improved from 56.52% to 90.72% and also the minimum possible efficiency with the spray cooling unit was 32.38% more efficient, indicating that the cooling process through spray cooling unit had a vast improvement on the efficiency of the intercooling system. It was decided that any of the chosen spray medium with the lowest concentration could be used in the optimized unit as they all needed at most 23 psi using 3 pumps, which was replaced by a new single pump in the optimized unit that was readily available in the market. However, it all comes down to the basis of cost and efficiency as the chemical compounds need to be bought but medium such as tap water is readily available.

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