Modeling and Optimizing Automotive Waste Recovery for Optimal Performance

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Abstract: It is vital to explore an effective way to capture waste heat from modern automobiles. This research outlines the current methods to harness that excess heat from the exhaust system and a proposal to use a high-efficiency printed-circuit heat exchanger (PCHE) to harness the heat. The research also revealed a unique iteration process that encompasses testing of the exchanger in a closed-loop steam system which would serve as the basis for future experiments. In lieu of experiments, data was collected from peer-reviewed research of other scientists to approximate the effectiveness and efficiency of the system. The following facts were theoretically revealed by the derived model. The theorized heat exchanger was found to have a maximum transfer rate of 510 kW while the maximum heat supplied by the exhaust is around 100 kW. The exchanger is sufficiently designed to capture energy wasted by the engine through the tail pipe. With a mass of 5.169 kg for the exchanger alone and the estimated amount of fluid, turbine, generator, and piping to be no more than 50 kg, the vehicle will experience very little mass increase.

Keywords: Heat exchanger, Efficiency, Waster recovery, Mass, fluid.

INTRODUCTION

According to an article published by the American Society of Mechanical Engineers (2012), internal combustion engines waste up 65 percent of their available energy in the form of heat [1]. Thus, by harnessing just 10 percent of this wasted energy would correspond to an overall efficiency gain of 18 percent in the production of mechanical energy from petrol. Internal combustion engines (ICEs) get rid of excess heat from two locations: the radiator and the tailpipe. According to Fraunhofer-Gesellschaft's article in Science Daily (2008), "about 30 percent is lost through the engine block and a further 30 to 35 percent as the exhaust fumes" (para. 2). More energy is lost through exhaust and temperatures can reach up to 1200 degrees Fahrenheit [3] (~650 Centigrade). This makes the tailpipe the ideal location for energy recovery, as a larger difference between cold and hot sides increases the Carnot efficiency for a heat engine.

Many methods have been attempted for this heat collection, including thermoelectric generators [4], BMW's Turbosteamer [5], and even water injected ICEs [6]. TEGs are made of tiny thermocouples that utilize the Seebeck effect to produce small currents. Each couple is run in series with its neighbor to produce some voltage. The problem with these systems is that a single TEG Peltier module is only up to 2 percent efficient with a temperature difference of 55 degrees centigrade. BMW's Turbosteamer essentially used a closed loop steam engine to produce steam from the exhaust gases to push a steam piston attached to the crankshaft [7]. This technique allowed the scientists to decrease the exhaust gas temperature from 800 to 50 degrees Centigrade according to thermal imaging [5]. They also found that the energy output of the exhaust ranges from about 10 kilowatts (kW) at 1000 rotations-per-minute (rpm) (idle-speed) to 100 kW at 6000 rpm (full load) [5]. This project never reach production, but BMW claimed that the Turbosteamer could increase the mechanical efficiency of their vehicles by between 10 and 15 percent [5]. Water-assisted ICEs utilize a reservoir to inject water in the combustion chamber in order to cool the engine [7]. The water hits its flash point, violently expanding the combustion chamber, applying force to the piston head as steam [7]. This technique is rarely used, except in racing vehicles for the power gains, due to consumers showing little interest in refueling both gas and water into their cars [7]. Thus, a closed system for generation would be ideal for the general public.

Each of these techniques have their flaws. TEGs provide an overly simplified solution for energy recovery, yet their efficiencies prove their uselessness with current technology. The Turbosteamer likely proved to be too costly and complicated to be implemented in modern vehicles. Further, this new system had to function properly to keep the engine

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from overheating, adding to the number of moving parts of a traditional engine [6]. Water-assisted engines seem to be the best option from the examples; however, just like the Turbosteamer, these systems are required to function to make the vehicle operable. Further, water-assist requires the refilling of a water reservoir by the user. Therefore, the ideal system operates independently from the rest of the vehicle; if the user does not maintain this system, the car should function normally. To model and optimizing the automotive waste recovery cycle a theoretical harnessed system was develop based on the heat produced by the automotive exhaust stroke. The tool of heat transfer and fluid dynamics were used in modeling and optimizing the performance of the design automotive waste recovery cycle.

METHODOLOGY

The proposed heat collection system will be closed-loop and not create a dependence of the car on this subsystem. Below is a diagram of the proposed heat collection system.

As can be seen from Figure **1**, hot exhaust flows through the heat exchanger, transferring its heat to the cool water from the reservoir. After becoming superheated, the water is expanded through the turbine that rotates a generator, charging the hybrid battery or running the hybrid electric motor. The steam/water mixture is sent to a condenser to decrease the mixture's temperature closer to ambient. Next, the liquid water goes into the water reservoir. The system has a few modes of operation, including closed-loop, open-loop, and fully off. Closed-loop mode means that the steam release valve is fully closed unless there is excess water being collected from the A/C condenser. At which point, the valve is opened to evacuate the steam, increasing the efficiency of the system by decreasing the cold side temperature. Open-loop mode consists of a regular refilling of the reservoir with water. The steam release valve is fully open, allowing steam to escape after generating electricity. Fully off mode consists of the check valve being closed before the heat exchanger and the steam release valve being open. This causes the reservoir to keep its contents while allow the steam to expand and escape to prevent bursting. Brine will be mixed into the reservoir in northern climates for the winter months. This will prevent freezing. It will not escape the system, as the heat exchanger essentially distills the water of impurities.

The research studies focused on the theoretical modeling of critical and empirical data based on heat exchangers and energy recovery processes which are in line with the second law of thermodynamics and the Kelvin–Planck Statement. It should be noted that every heat engine must water some form of energy by transferring the energy to a low-temperature reservoir/system for complete idealized cycle conditions to hold. This fundamental principle is not validated in the proposed heat exchanger design model. The effect of change in temperature on mass flow there were constant based on model and factual relationship are shown in equation 1 and 2.

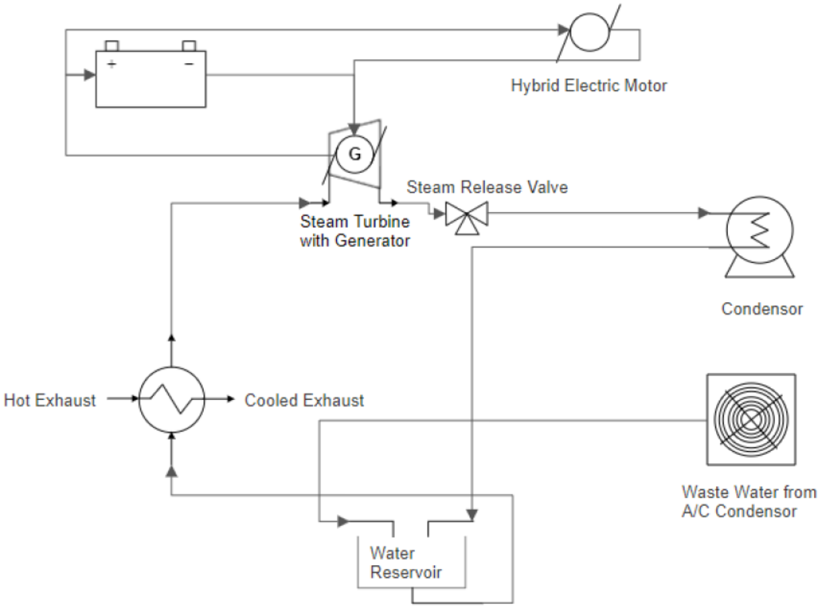


Figure 1: Diagram of proposed heat collection system.

Within the scope of the project, only the heat exchanger of the proposed system will be idealized for modern vehicles. Ideally, this heat exchanger would prevent excessive pressure drop. Thus, the cross section of the exhaust pipe flow should be maintained before and after the exchanger. Different operating temperatures and speeds must be accounted for. The data from the BMW study of the Turbosteamer shows the maximum heat transfer of the exhaust gases to be 100 kW. Thus, this will be the maximum design parameter for the necessary heat transfer of the heat exchanger.

$$Q = \dot{m}_w c_w \left(T_{2,w} - T_{1,w}\right) = \dot{m}_w c_w \left(T_{2,exh} - T_{1,exh}\right) \tag{1}$$

where c is the specific heat, $\dot{m}$ is the mass flow rate, and T is the temperature

Equation 1 can be rearranged to solve for the mass flow of each fluid.

$$\dot{m}_w = \frac{Q}{c_w\left(T_{w,out} - T_{w,in}\right)}, \dot{m}_{exh} = \frac{Q}{c_w\left(T_{exh,out} - T_{exh,in}\right)} \tag{2}$$

Finding the velocity of each fluid from the mass flow rate is essential to finding the Reynold number. Equation 3 shows the finding of velocity below. Equation 4 shows the finding of the Reynold number.

$$\vec{V} = \frac{\dot{m}}{\rho A} \tag{3}$$

where ρ is the density of the fluid, A is the effective cross-sectional area of flow. The cross-section of flow will be consistent before, during, and after the heat exchanger to prevent any pressure differences. For the sake of calculation, the assumed diameter is 90 mm, thus a cross-section of 0.00636 square-meters. Exhaust gas is made of many different gases. A Table **1** below gives their relative composition [9].

Table 1: Relative gas composition of exhaust gas [9]

Gas	% Of Total Composition
Nitrogen	71
Carbon Dioxide	14
Water Vapor	13
Carbon Monoxide	2

Thus, the overall properties of exhaust gas will be assumed to be the proportional sum of the properties of the individual gases. Table A contains the properties of the individual gases. The assumed starting temperature of the exhaust gas is assumed to be 650 degrees centigrade [3] and the water is at ambient room temperature. Table **2** gives these properties below.

Table 2: Assumed Properties of Exhaust Gases and Water at 650 Degrees Celsius

Fluid	Properties	Value
Water	ρ	997.6 kg/m^3
	k	0.6016 W/m*K
	C	4181.2 J/kg*K
	v	0.0009576
	Prandtl	6.662
	T_1	22*C
	T_2	400*C
	A	0.00636 m^2
Exhaust gas	ρ	0.2459 kg/m^3
	k	0.09439 W/m*K
	C	1420.7 J/kg*K
	v	0.000216
	Prandtl	0.6995
	T_1	650*C
	T_2	22*C
	A	0.00636 m^2

Thus, the values can be plugged into Equations 2 and 3 to yield the following.

Table 3: Calculated Mass Flow, Velocity, and Reynolds Number

Fluid	Properties	Value
Water	$\dot{m}$	0.06327 kg/s
	$\vec{V}$	0.00997 m/s
	Re	4181.2 J/kg*K
Exhaust gas	$\dot{m}$	0.1121 kg/s
	$\vec{V}$	71.67 m/s
	Re	4181.2 J/kg*K

Using the cross-section of the exhaust pipe in order to prevent pressure drop, the PCHE was created below using Autodesk Inventor 2022.

As can be seen from Figure **2**, the theoretical PCHE is a simple crossflow exchanger between water, the

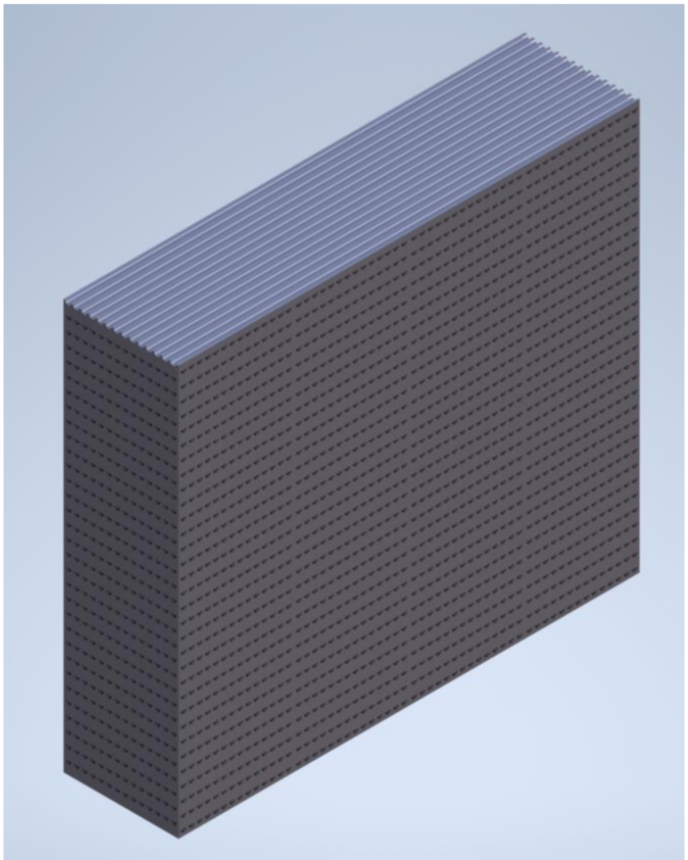


Figure 2: Designed PCHE.

working fluid for energy regeneration, and exhaust gases. The exhaust gases flow through the largest cross-section, as the heat transfer coefficient for gases are usually much lower than liquids. The assemble heat exchanger can be seen below in Figure **3**.

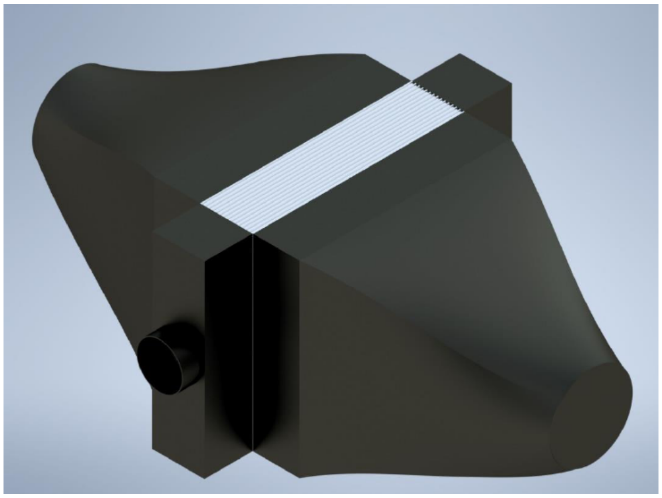


Figure 3: Theoretical heat exchanger.

This research is based on the application of previously designed PCHEs and the theoretical application of its heat transfer coefficient. Physical experimentation was not performed for the synthesis of this paper due to lack of funding. If data validation was desired, a PCHE could be manufactured and tested to find its heat transfer coefficient for the proposed design. Instead, for the sake of this study, the standard transfer coefficients for PCHEs were used, as the calculations for this specific exchanger are very complex. A study done in 2018 by the University of Michigan was a benchmark in this research since it was found that the heat transfer coefficient for such a system is approximately 2500 W/m^2-K [11]. With a total surface area of 0.82 m^2 for this heat exchanger, the mass energy transfer can be found using the equation below.

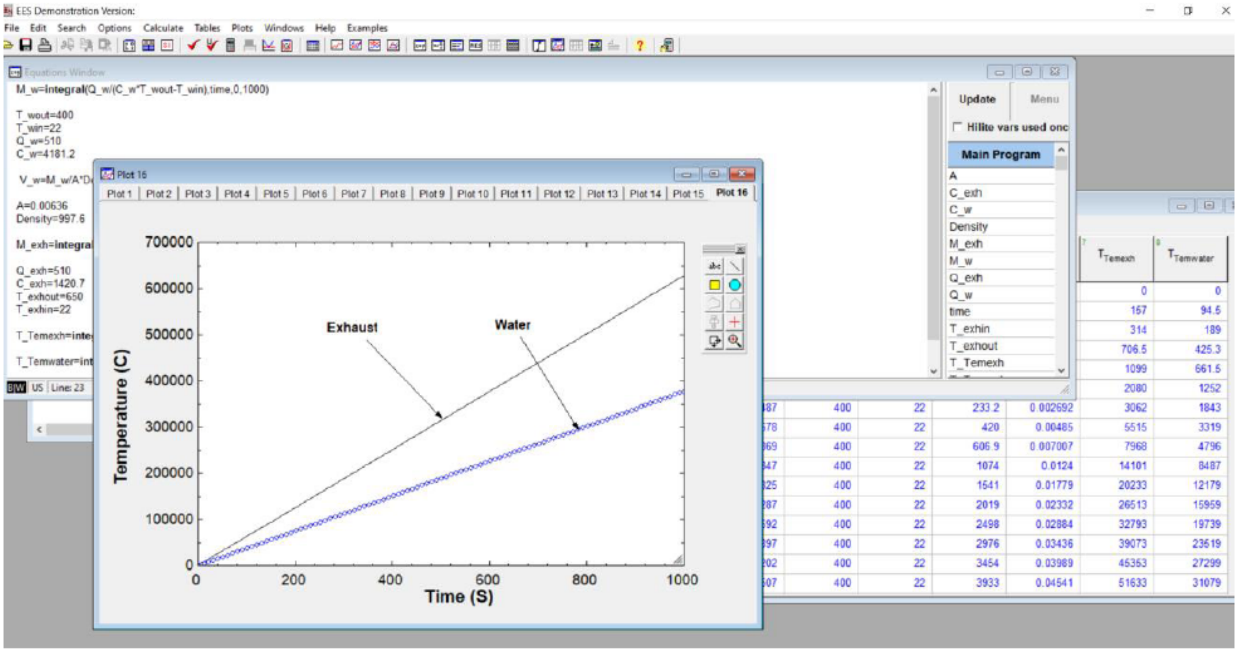
$$\dot{Q} = hA_s(T_{h,exh} - T_{h,w}) \tag{4}$$

$$\dot{Q} = 2500\left[\frac{\mathrm{W}}{\mathrm{m}^2\cdot\mathrm{K}}\right]\cdot 0.82\,[\mathrm{m}^2]\cdot(650\,[^\circ\mathrm{C}] - 400\,[^\circ\mathrm{C}]) = 510\ \mathrm{kW}$$

The reason 400 degrees Celsius is used for the water temperature is since steam turbines tend to run more efficiently at that temperature [12]. In order to keep the exhaust at such a high temperature, the exhaust pipe will have to be sufficiently insulated before its connection to the PCHE. Equations (1) to (4) are solved simultaneously using Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) while employing the parameters and data shown in Table **3**. Thus, the proposed models in this reported are tested with previous data from Turbosteamer.

RESULTS AND DISCUSSION

It should be observed from Figure **4**(**a**-**b**) that the natures of temperature evolution of time increased more on the exhaust flow when compared to water flow during engine operation. The obtained results are in line with the theory Newtonian fluid flow and heat transfer process due to change in flow properties caused by the variation of flow coefficient and stress-strain factors on the fluid flow line. The temperature is



```
M_w=integral(Q_w/(C_w*T_wout-T_win),time,0,1000)

T_wout=400
T_win=22
Q_w=510
C_w=4181.2

 V_w=M_w/A*D

A=0.00636
Density=997.6

M_exh=integral

Q_exh=510
C_exh=1420.7
T_exhout=650
T_exhin=22

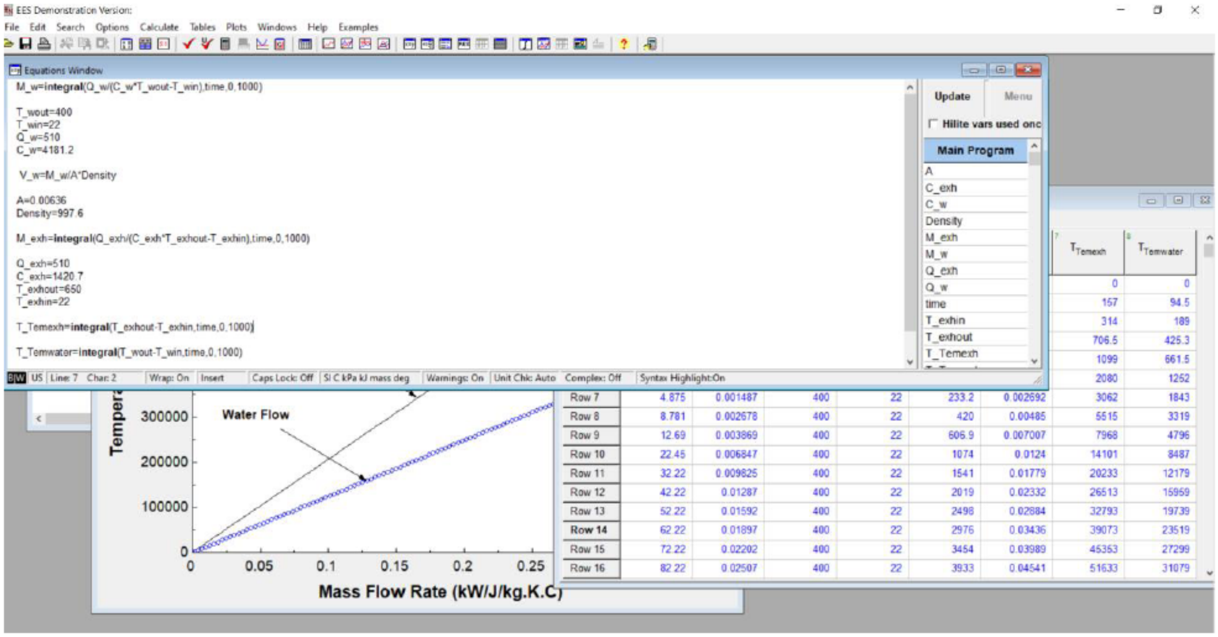
T_Temexh=inte

T_Temwater=int
```

Main Program
A
C_exh
C_w
Density
M_exh
M_w
Q_exh
Q_w
time
T_exhin
T_exhout
T_Temexh

					T_{Temexh}	$T_{Temwater}$
					0	0
					157	94.5
					314	189
					706.5	425.3
					1099	661.5
					2080	1252
87	400	22	233.2	0.002692	3062	1843
78	400	22	420	0.00485	5515	3319
69	400	22	606.9	0.007007	7968	4796
47	400	22	1074	0.0124	14101	8487
25	400	22	1541	0.01779	20233	12179
87	400	22	2019	0.02332	26513	15959
92	400	22	2498	0.02884	32793	19739
97	400	22	2976	0.03436	39073	23519
02	400	22	3454	0.03989	45363	27299
07	400	22	3933	0.04541	51633	31079

(a)



```
M_w=integral(Q_w/(C_w*T_wout-T_win),time,0,1000)

T_wout=400
T_win=22
Q_w=510
C_w=4181.2

 V_w=M_w/A*Density

A=0.00636
Density=997.6

M_exh=integral(Q_exh/(C_exh*T_exhout-T_exhin),time,0,1000)

Q_exh=510
C_exh=1420.7
T_exhout=650
T_exhin=22

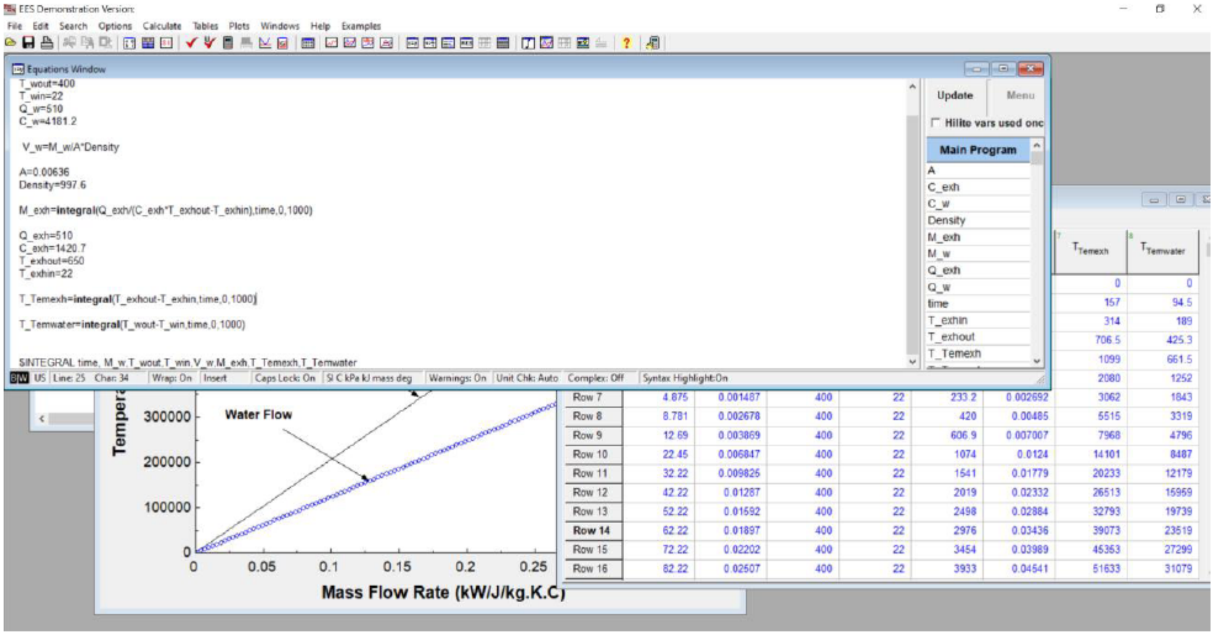
T_Temexh=integral(T_exhout-T_exhin,time,0,1000)

T_Temwater=integral(T_wout-T_win,time,0,1000)
```

Main Program
A
C_exh
C_w
Density
M_exh
M_w
Q_exh
Q_w
time
T_exhin
T_exhout
T_Temexh

							T_{Temexh}	$T_{Temwater}$
							0	0
							157	94.5
							314	189
							706.5	425.3
							1099	661.5
							2080	1252
Row 7	4.875	0.001487	400	22	233.2	0.002692	3062	1843
Row 8	8.781	0.002678	400	22	420	0.00485	5515	3319
Row 9	12.69	0.003869	400	22	606.9	0.007007	7968	4796
Row 10	22.45	0.006847	400	22	1074	0.0124	14101	8487
Row 11	32.22	0.009825	400	22	1541	0.01779	20233	12179
Row 12	42.22	0.01287	400	22	2019	0.02332	26513	15959
Row 13	52.22	0.01592	400	22	2498	0.02884	32793	19739
Row 14	62.22	0.01897	400	22	2976	0.03436	39073	23519
Row 15	72.22	0.02202	400	22	3454	0.03989	45363	27299
Row 16	82.22	0.02507	400	22	3933	0.04541	51633	31079

(b)



```
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Q_w=510
C_w=4181.2

 V_w=M_w/A*Density

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Density=997.6

M_exh=integral(Q_exh/(C_exh*T_exhout-T_exhin),time,0,1000)

Q_exh=510
C_exh=1420.7
T_exhout=650
T_exhin=22

T_Temexh=integral(T_exhout-T_exhin,time,0,1000)

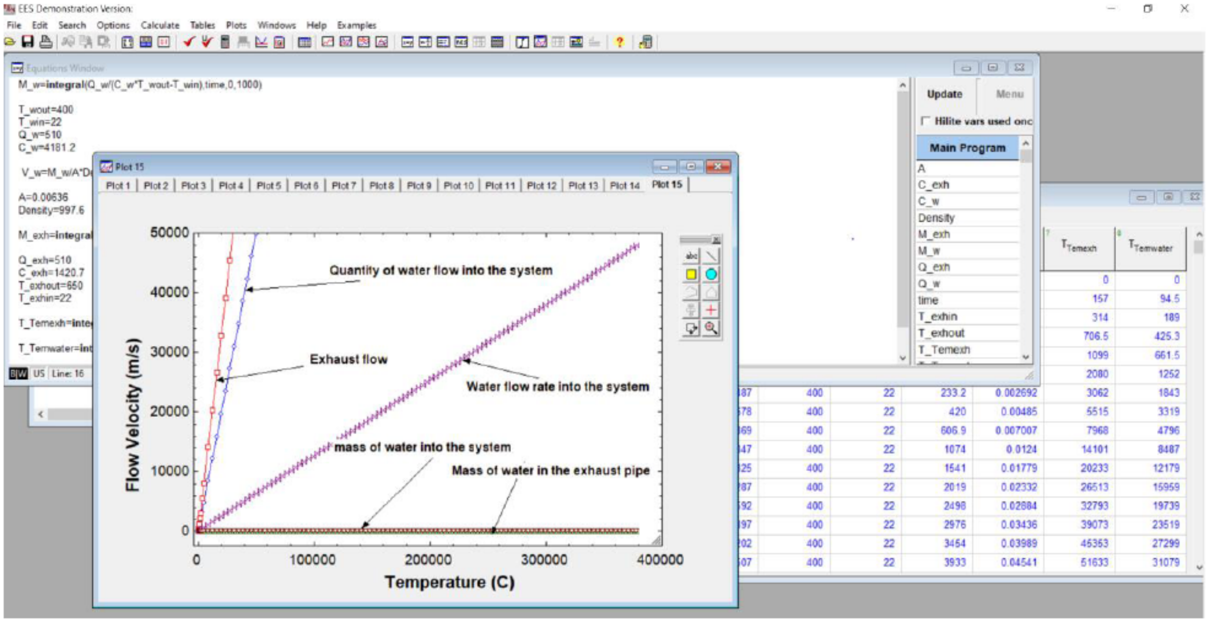
T_Temwater=integral(T_wout-T_win,time,0,1000)


$INTEGRAL time, M_w,T_wout,T_win,V_w,M_exh,T_Temexh,T_Temwater
```

B|W US Line: 25 Char: 34 Wrap: On Insert Caps Lock: On SI C kPa kJ mass deg Warnings: On Unit Chk: Auto Complex: Off Syntax Highlight:On

							T_Temexh	T_Temwater
							0	0
							157	94.5
							314	189
							706.5	425.3
							1099	661.5
							2080	1252
Row 7	4.875	0.001487	400	22	233.2	0.002692	3062	1843
Row 8	8.781	0.002678	400	22	420	0.00485	5515	3319
Row 9	12.69	0.003869	400	22	606.9	0.007007	7968	4796
Row 10	22.45	0.006847	400	22	1074	0.0124	14101	8487
Row 11	32.22	0.009825	400	22	1541	0.01779	20233	12179
Row 12	42.22	0.01287	400	22	2019	0.02332	26513	15959
Row 13	52.22	0.01592	400	22	2498	0.02884	32793	19739
Row 14	62.22	0.01897	400	22	2976	0.03436	39073	23519
Row 15	72.22	0.02202	400	22	3454	0.03989	45353	27299
Row 16	82.22	0.02507	400	22	3933	0.04541	51633	31079

(c)



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Density=997.6

M_exh=integral

Q_exh=510
C_exh=1420.7
T_exhout=650
T_exhin=22

T_Temexh=inte

T_Temwater=int
```

B|W US Line: 16

					0	0
					157	94.5
					314	189
					706.5	425.3
					1099	661.5
					2080	1252
87	400	22	233.2	0.002692	3062	1843
78	400	22	420	0.00485	5515	3319
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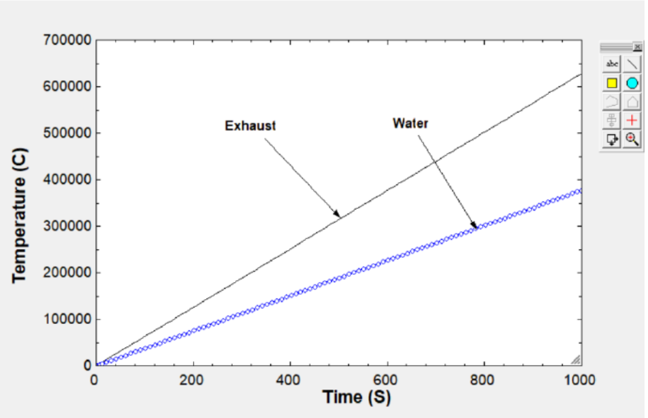
02	400	22	3454	0.03989	45353	27299
07	400	22	3933	0.04541	51633	31079

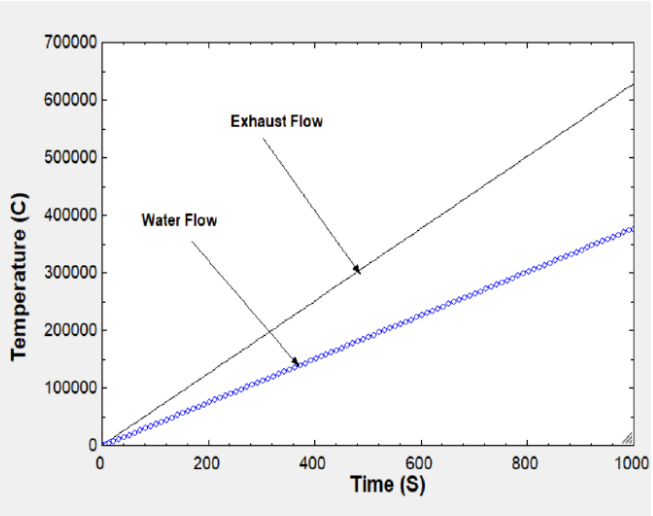
(d)

Figure 4: (**a**-**d**) Engineering Equation Solver software (F-Chart Software, Madison, W153744, USA) simulation.

observed to increase more during exhaust stroke due to high expansion process in the cylinder that is accompanied by increased in heat flow and heat transfer during engine operation. The model and simulation of the theorized heat exchanger was found to have a maximum transfer temperature on the exhaust stroke. Thus, the exchanger is sufficiently designed to capture energy wasted by the engine through the tail pipe. The temperature of water is lower than that of the heat exchange. Due to the fact that with a mass of 5.169 kg for the exchanger alone and the estimated amount of fluid, turbine, generator, and piping to be no more than 50 kg, the vehicle will experience very little mass increase. Due to low properties (temperature and fluid density), the flow velocity and mass flow rate of the system are affected as shown in Figure **5** (**a-c**)

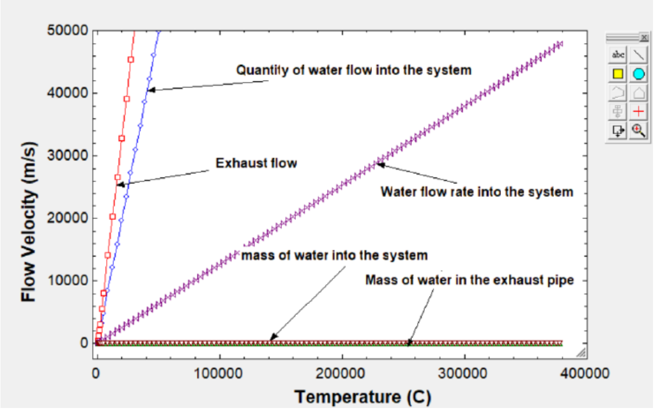


(a)

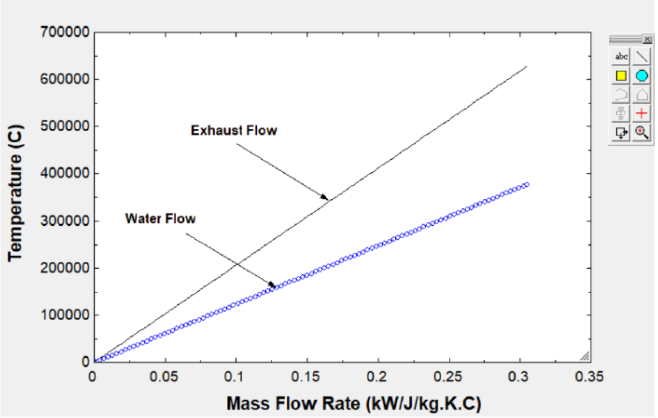


(b)

Figure 5: (**a**) Temperature evolutions of Time for exhaust and water (**b**) Temperature evolution of time for exhaust flow and water flow.



(a)



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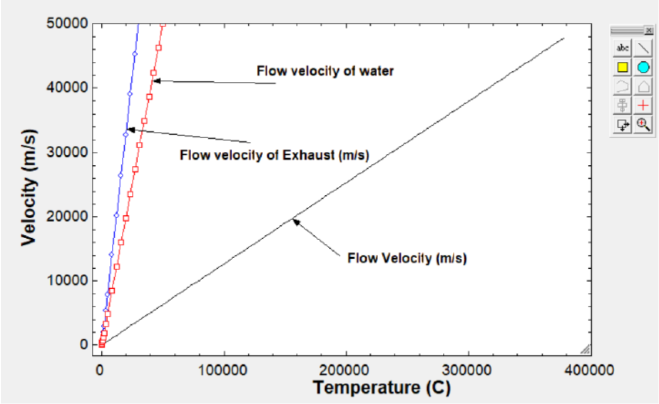


(c)

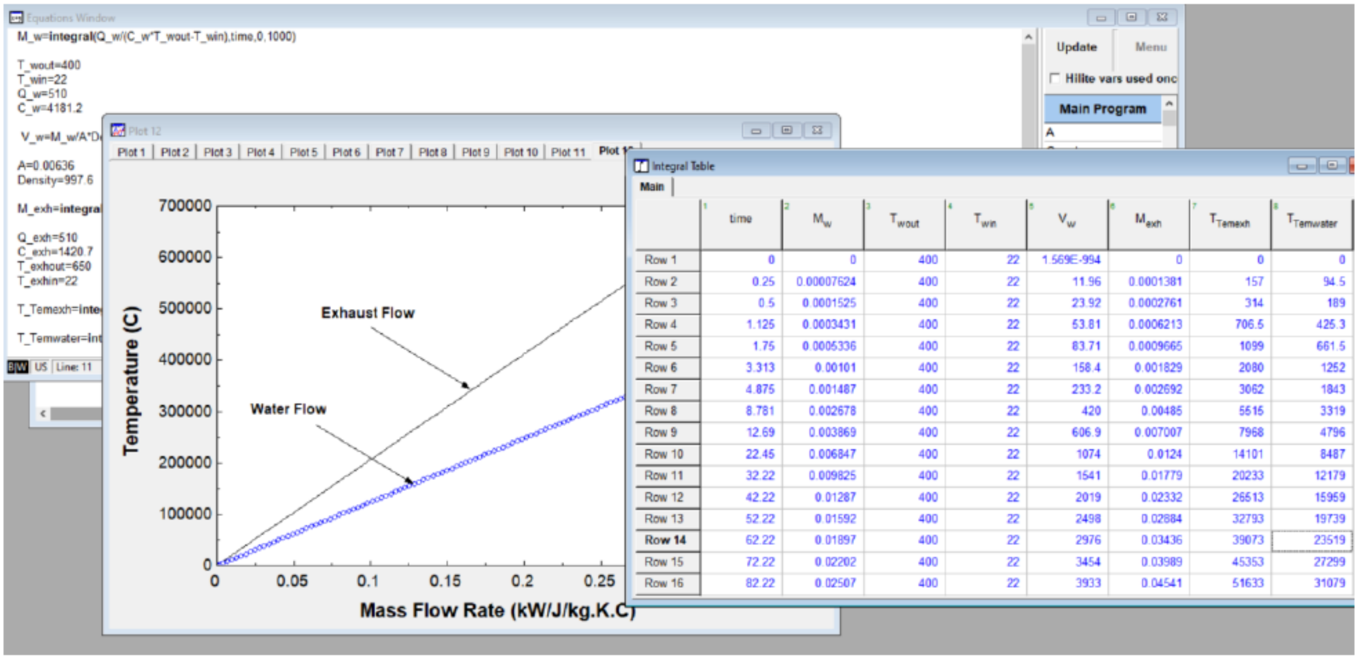
Figure 6: (**a**) Mass Flow rate evolutions of velocity (**b**) mass flow rate evolution of temperature and velocity evolution of temperature.

It is shown from Figure **6**(**a**-**c**) that, properties vary due change in temperature for exhaust and water flow during the cycle of operation. It is observed that, at a temperature of, for example, 100 °C, different flow velocities are obtained for exhaust flow, quantity of water flow into the system, and mass flow rate of water into the system. The nature of the evolution exhaust flow, quantity of water flow into the system, and mass flow rate of water into the system depends on thermal coefficient of heat exchange process, designed capture wasted of wasted energy ratio, by the engine through the tail pipe and the cross-sectional area of flow through the heat exchanger equaling that of the exhaust pipe. The exhaust flow line is observed to evolved with the highest flow velocity which is followed by the quantity of water flow onto the system and followed by the water flow into the system and the least were mass of water into the system and mass of water in the exhaust pipe as shown in Figure **6**(**a**-**c**).

APPENDIX A: PROPERTIES OF GASES AT 1 ATMOSPHERIC [10]

Temperature	Composition	Specific Heat	Density	Kinematic Viscosity	Prandtl	Thermal Conductivity
Centigrade		c, J/kg*K	kg/cu-m	*v*, m^2/s		*K*, W/m*K
Nitrogen						
-50	0.71	957.3	1.5299	9.091E-06	0.6655	0.02001
0	0.71	1035	1.2498	0.00001312	0.7121	0.02384
50	0.71	1042	1.0564	0.00001774	0.7114	0.02746
100	0.71	1041	0.9149	0.00002289	0.7056	0.0309
150	0.71	1043	0.8068	0.00002851	0.7025	0.03416
200	0.71	1050	0.7215	0.00003457	0.7025	0.03727
300	0.71	1070	0.5956	0.00004783	0.7078	0.04309
400	0.71	1095	0.5072	0.00006242	0.7153	0.04848
500	0.71	1120	0.4416	0.00007816	0.7215	0.05358
1000	0.71	1213	0.2681	0.0001713	0.7022	0.07938
1500	0.71	1266	0.1925	0.0002889	0.5969	0.11793
2000	0.71	1297	0.1502	0.0004278	0.4483	0.1859
Carbon Dioxide						
-50	0.14	746	2.4035	0.00004699	0.8019	0.01051
0	0.14	811	1.9635	0.00001375	0.7661	0.01456
50	0.14	866.6	1.6597	0.00001612	0.752	0.01858
100	0.14	914.8	1.4373	0.00001841	0.7464	0.02257
150	0.14	957.4	1.2675	0.00002063	0.7445	0.02652
200	0.14	995.2	1.1336	0.00002276	0.7442	0.03044
300	0.14	1060	0.9358	0.00002682	0.745	0.03814
400	0.14	1112	0.7968	0.00003061	0.7458	0.04565
500	0.14	1156	0.6937	0.00003416	0.746	0.05293
1000	0.14	1292	0.4213	0.00004898	0.7455	0.08491
1500	0.14	1356	0.3025	0.00006106	0.7745	0.10688
2000	0.14	1387	0.2359	0.00007322	0.8815	0.11522
Water Vapor						
-50	0.13	1892	0.9839	7.305E-06	1.0047	0.01051
0	0.13	1874	0.8038	0.00001114	1.0033	0.01456
50	0.13	1874	0.6794	0.00001587	0.9944	0.01858
100	0.13	1887	0.5884	0.0000215	0.983	0.02257
150	0.13	1908	0.5189	0.00002806	0.9712	0.02652
200	0.13	1935	0.464	0.00003556	0.9599	0.03044
300	0.13	1997	0.3831	0.0000534	0.9401	0.03814
400	0.13	2066	0.3262	0.00007498	0.924	0.04565
500	0.13	2137	0.284	0.0001002	0.9108	0.05293

1000	0.13	2471	0.1725	0.0002761	0.8639	0.08491
1500	0.13	2736	0.1238	0.0005177	0.8233	0.10688
2000	0.13	2928	0.0966	0.0008084	0.7833	0.11522
Carbon Monoxide						
-50	0.02	1081	1.5297	9.012E-06	0.784	0.01901
0	0.02	1048	1.2497	0.00001303	0.7499	0.02278
50	0.02	1039	1.0563	0.00001764	0.7328	0.02641
100	0.02	1041	0.9148	0.00002274	0.7239	0.02992
150	0.02	1049	0.8067	0.0000283	0.7191	0.033
200	0.02	1060	0.7214	0.00003426	0.7164	0.3656
300	0.02	1085	0.5956	0.00004722	0.7134	0.04277
400	0.02	1111	0.5071	0.00006136	0.7111	0.0486
500	0.02	1135	0.4415	0.00007653	0.7087	0.05412
1000	0.02	1226	0.2681	0.00017	0.708	0.07894
1500	0.02	1279	0.1925	0.0003284	0.7733	0.10458
2000	0.02	1309	0.1502	0.0006543	0.9302	0.13833



```
M_w=integral(Q_w/(C_w*T_wout-T_win),time,0,1000)

T_wout=400
T_win=22
Q_w=510
C_w=4181.2

 V_w=M_w/A*D

A=0.00636
Density=997.6

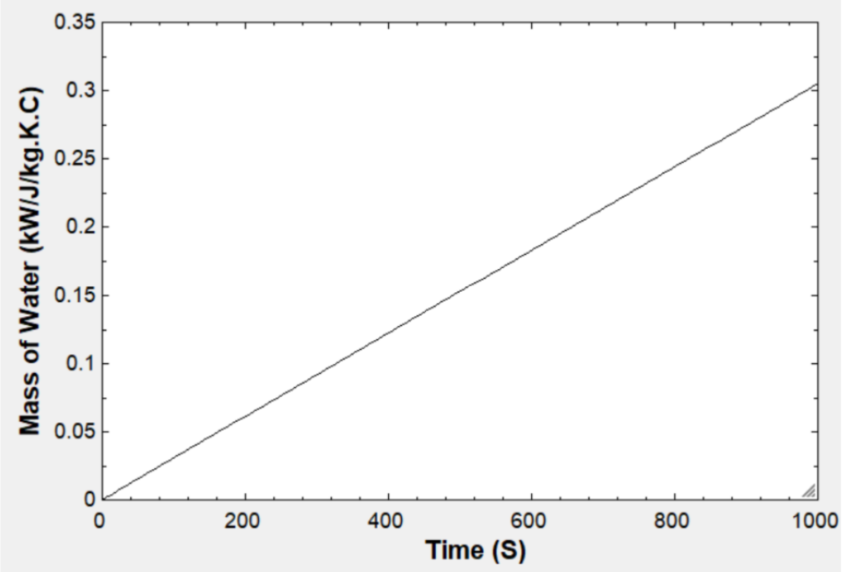
M_exh=integral

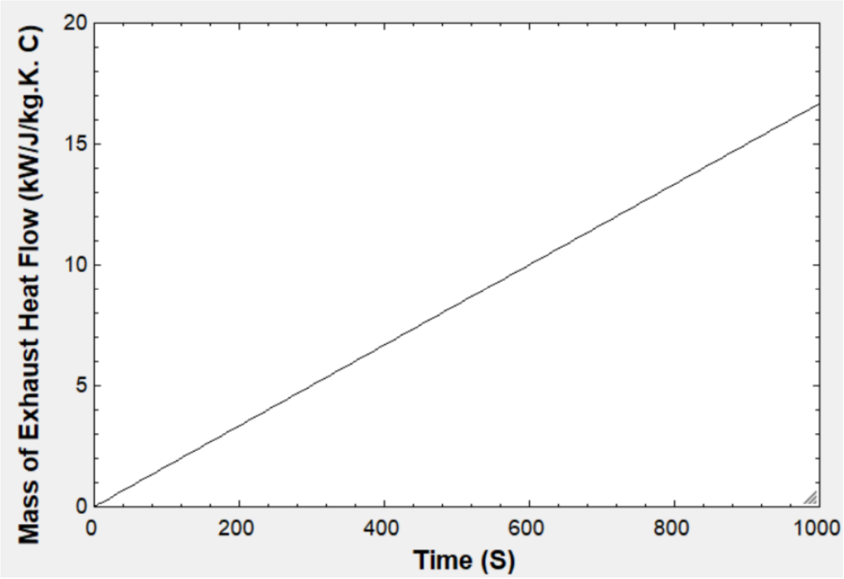
Q_exh=510
C_exh=1420.7
T_exhout=650
T_exhin=22

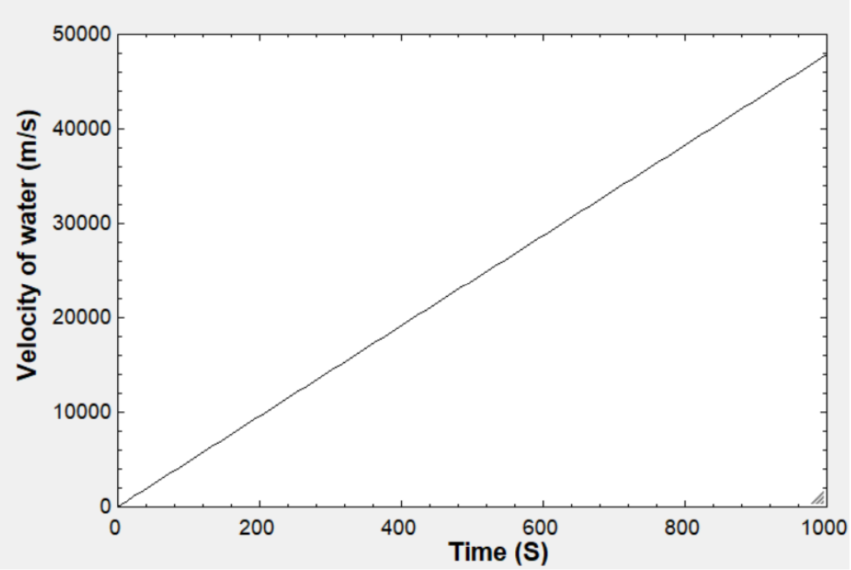
T_Temexh=inte

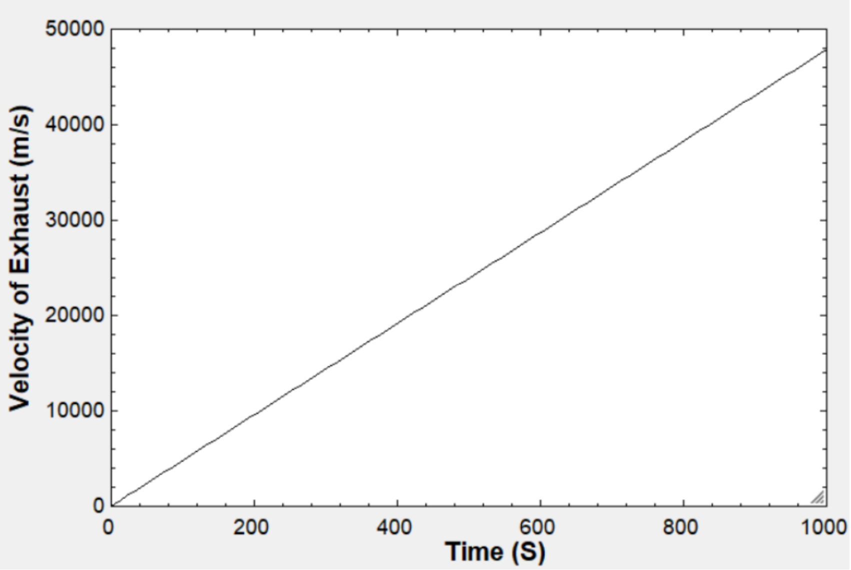
T_Temwater=in
```

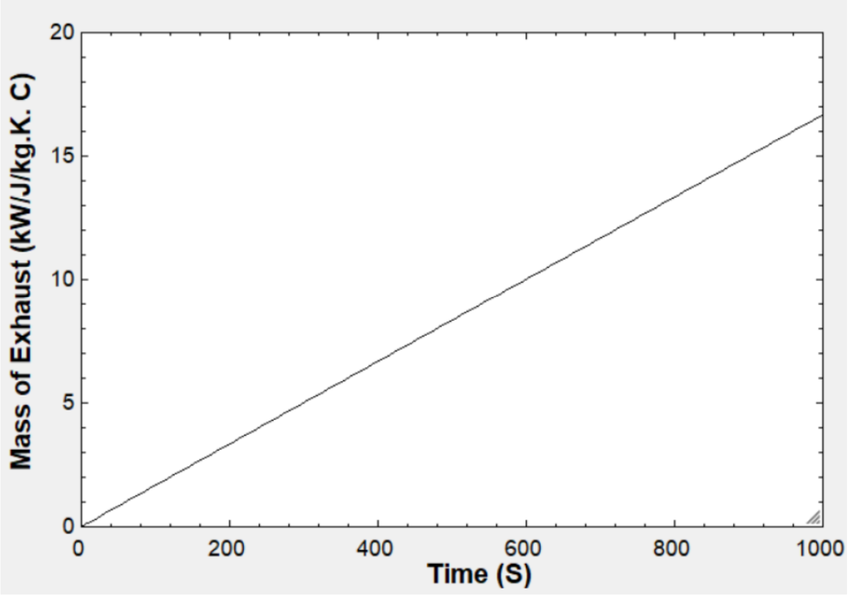
	1 time	2 M_w	3 T_{wout}	4 T_{win}	5 V_w	6 M_{exh}	7 T_{Temexh}	8 $T_{Temwater}$
Row 1	0	0	400	22	1.569E-994	0	0	0
Row 2	0.25	0.00007624	400	22	11.96	0.0001381	157	94.5
Row 3	0.5	0.0001525	400	22	23.92	0.0002761	314	189
Row 4	1.125	0.0003431	400	22	53.81	0.0006213	706.5	425.3
Row 5	1.75	0.0005336	400	22	83.71	0.0009665	1099	661.5
Row 6	3.313	0.00101	400	22	158.4	0.001829	2080	1252
Row 7	4.875	0.001487	400	22	233.2	0.002692	3062	1843
Row 8	8.781	0.002678	400	22	420	0.00485	5516	3319
Row 9	12.69	0.003869	400	22	606.9	0.007007	7968	4796
Row 10	22.45	0.006847	400	22	1074	0.0124	14101	8487
Row 11	32.22	0.009825	400	22	1541	0.01779	20233	12179
Row 12	42.22	0.01287	400	22	2019	0.02332	26513	15959
Row 13	52.22	0.01592	400	22	2498	0.02884	32793	19739
Row 14	62.22	0.01897	400	22	2976	0.03436	39073	23519
Row 15	72.22	0.02202	400	22	3454	0.03989	45353	27299
Row 16	82.22	0.02507	400	22	3933	0.04541	51633	31079

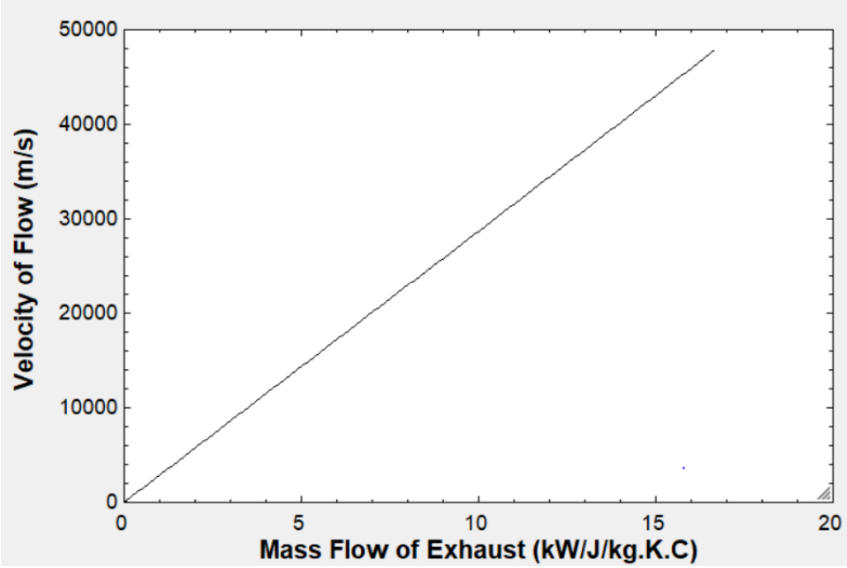

Mass of Water (kW/J/kg.K.C)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
Time (S)

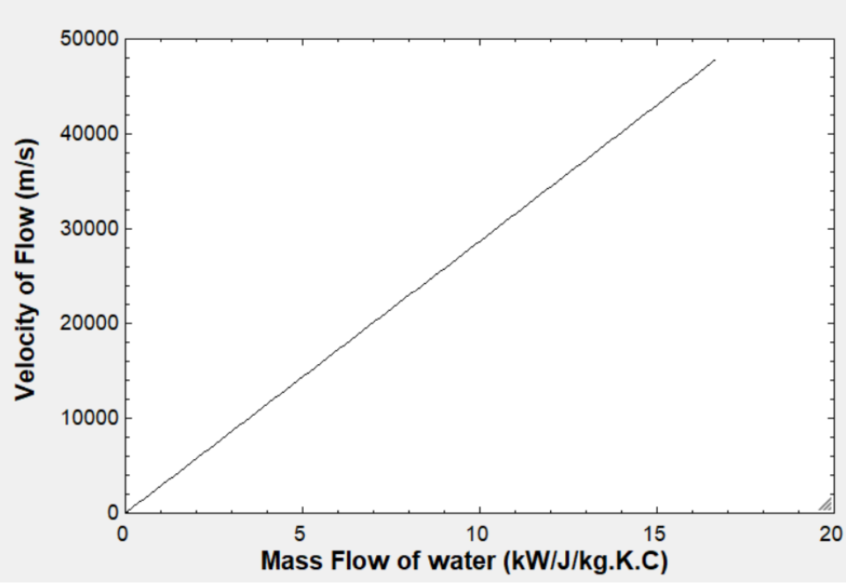

Mass of Exhaust Heat Flow (kW/J/kg.K. C)
20
15
10
5
0
0
200
400
600
800
1000
Time (S)

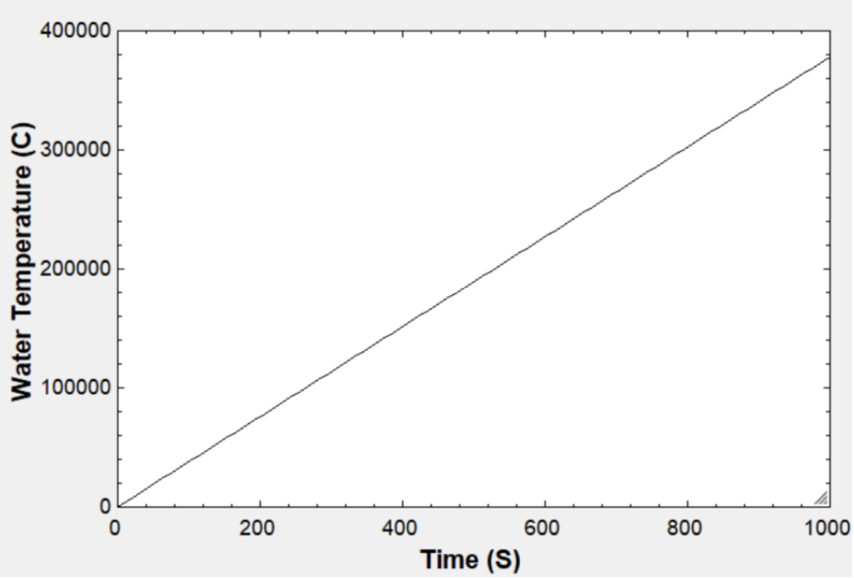

Velocity of water (m/s)
50000
40000
30000
20000
10000
0
0
200
400
600
800
1000
Time (S)

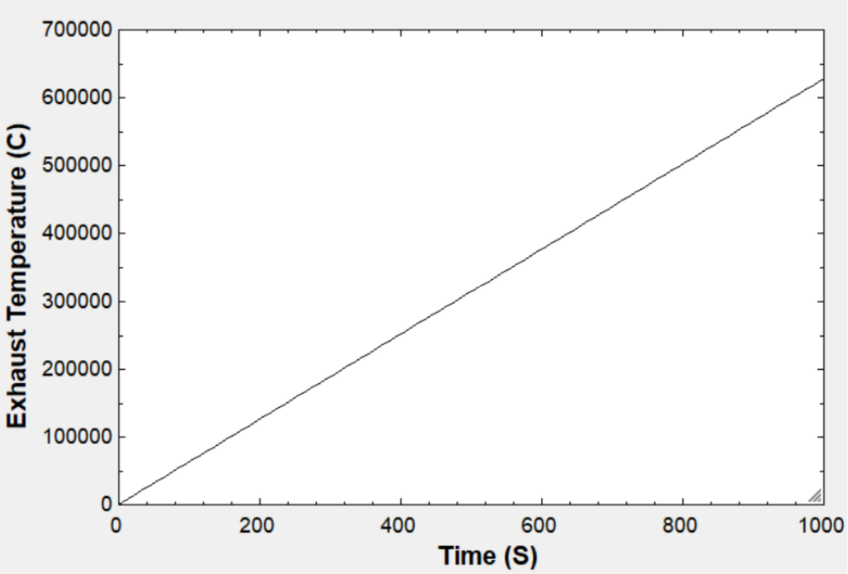

Velocity of Exhaust (m/s)
50000
40000
30000
20000
10000
0
0
200
400
600
800
1000
Time (S)

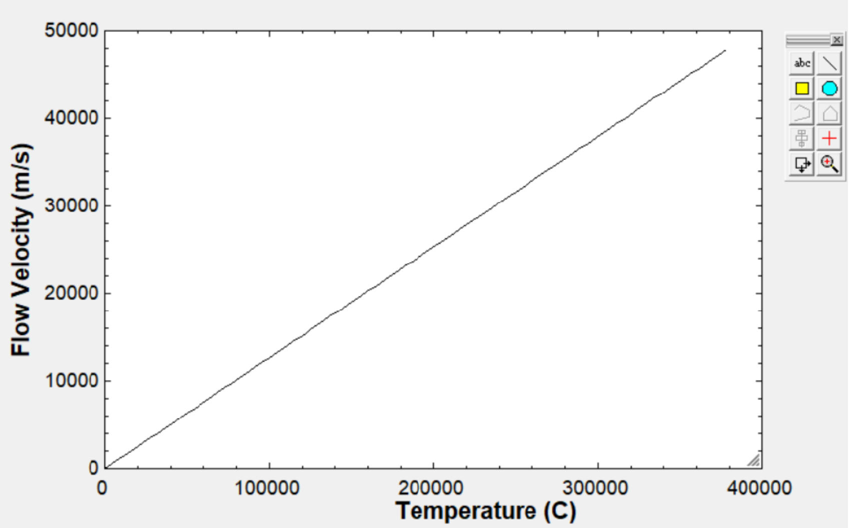

Mass of Exhaust (kW/J/kg.K. C)
20
15
10
5
0
0
200
400
600
800
1000
Time (S)


Velocity of Flow (m/s)
50000
40000
30000
20000
10000
0
0
5
10
15
20
Mass Flow of Exhaust (kW/J/kg.K.C)


50000
40000
30000
20000
10000
0
Velocity of Flow (m/s)
0
5
10
15
20
Mass Flow of water (kW/J/kg.K.C)


400000
300000
200000
100000
0
Water Temperature (C)
0
200
400
600
800
1000
Time (S)


700000
600000
500000
400000
300000
200000
100000
0
Exhaust Temperature (C)
0
200
400
600
800
1000
Time (S)



The theorized heat exchanger was found to have a maximum transfer rate of 510 kW while the maximum heat supplied by the exhaust is around 100 kW. Thus, the exchanger is sufficiently designed to capture energy wasted by the engine through the tail pipe. Due to the cross-sectional area of flow through the heat exchanger equaling that of the exhaust pipe, little pressure drop is to be expected, allowing the engine to not feel the effects of back-pressure. Assuming the rest of the system to be at most 20 percent efficient, the system would yield 20 kW of power back to the vehicle at full throttle. With a mass of 5.169 kg for the exchanger alone and the estimated amount of fluid, turbine, generator, and piping to be no more than 50 kg, the vehicle will experience very little mass increase. Assuming the average rpm of a vehicle's engine to be 2500 rpm, corresponding to an exhaust heat output of 20 kW, over the course of a one-hour drive, the system will recover 4 kWh of energy. Based on the Environmental Protection Agency's (EPA) conversion of electrical energy to gasoline of 33.705 kWh per gallon of gasoline,[13] the system will save about 0.12 gallons of gasoline per hour driven. At standard rural highway speeds of around 60 mph and the average fuel economy of a car in the US being 25.4 miles-per-gallon (mpg) in 2022,[14] this system would add an extra 3 miles per gallon, a 12 percent increase in fuel economy. A significant increase in fuel economy would result in lower fuel costs and lower overall fuel emissions. According to MIT, standard PCHEs cost less than $0.05/W.[14] Thus, this specific exchanger being able to transfer 510 kW at 5 cents per watt would cost $25,000. This exceeds the cost of many cars! Even if this over-engineered design was cut down to only transfer 50 kW, just the exchanger alone would cost 2,500 dollars. For this technology to become viable in future, more research will need to be performed to create cost-effective PCHEs for consumer usage. PCHE technology is still rather new, being around 30 years old. As the materials for the exchanger are rather basic, being copper or copper-alloy, most cost efficacy may come from cheaper manufacturing processes as the tooling for such exchangers becomes lower as demand rises.

CONCLUSION

The objectives of this paper were met as a system was designed to recover energy losses from exhaust systems, a heat exchanger was designed to work with the average automobile's needs, and the future implications of such a device were analyzed. To achieve this, a theoretical model was derived based on the functionality of the heat flow through an automotive exhaust pipe. The derived model was established based heat transfer and fluid flow during the exhaust stroke. It was shown that, the theorized heat exchanger was found to have a maximum transfer rate of 510 kW while the maximum heat supplied by the exhaust is around 100 kW. Thus, the exchanger is sufficiently designed to capture energy wasted by the engine through the tail pipe. Due to the cross-sectional area of flow through the heat exchanger equaling that of the exhaust pipe, little pressure drop is to be expected, allowing the engine to not feel the effects of back-pressure. Assuming the rest of the system to be at most 20 percent efficient, the system would yield 20 kW of power back to the vehicle at full throttle. With a mass of 5.169 kg for the exchanger alone and the estimated amount of fluid, turbine, generator, and piping to be no more than 50 kg, the vehicle will experience very little mass increase. Assuming the average rpm of a vehicle's engine to be 2500 rpm, corresponding to an exhaust heat output of 20 kW, over the course of a one-hour drive, the system will recover 4 kWh of energy.

REFERANCES

[1] Sniderman, D. (2012). Using waste engine heat in automobile engines. https://www.asme.org/topics-resources/content/using-waste-engine-heat-in-automobile-engines#:~:text=most%20effective%20way.-,Currently%2C%20up%20to%2065%25%20of%20the%20heat%20energy%20produced%20in,internal%20combustion%20engines%20is%20wasted

[2] Fraunhofer-Gesellschaft (2008, June 4). Electricity from the exhaust pipe. www.sciencedaily.com/releases/2008/06/080603110849.htm

[3] Surface temperatures: Underhood. (n. d.). https://depts.washington.edu/vehfire/ignition/autoignition/surftemper.html#:~:text= Manifolds%20and%2For%20exhaust%20pipes,or%20impingement%20of%20exhaust%20gas.

[4] L.S. Hewawasam, A.S. Jayasena, M.M.M. Afnan, R.A.C.P. Ranasinghe, M.A. Wijewardane (2020). Waste heat recovery from thermo-electric generators (TEGs), Energy Reports, 6(2): 474-479. https://doi.org/10.1016/j.egyr.2019.11.105

[5] Obieglo, J. Ringler, M. Seifert, W. Hall (2009). Future efficient dynamics with heat recovery. https://www.energy.gov/sites/prod/files/2014/03/f8/deer09_obieglo.pdf

[6] S. Zhu, B. Hu, S. Akehurst, C. Copeland, A. Lewis, H. Yuan, I. Kennedy, J. Bernards, C. Branney (2019). A review of water injection applied on the internal combustion engine, Energy Conversion and Management 184(1): 139-158. https://doi.org/10.1016/j.enconman.2019.01.042

[7] M. Hanlon (2005). BMW unveils the turbosteamer concept. https://newatlas.com/go/4936/

[8] L.O. Freire, L.M. Navarrete, B.P. Corrales, J.N. Castillo (2021). Efficiency in thermoelectric generators based on Peltier cells, Energy Reports, 7(3): 355-361. https://doi.org/10.1016/j.egyr.2021.08.099

[9] Exhaust gas. (2022, Apr 10). In Wikipedia. https://en.wikipedia.org/wiki/Exhaust_gas.

[10] Y.A. Cengel, J.M. Cimbala, R.H. Turner (2012). Fundamentals of thermal-fluid sciences (5th ed.). McGraw-Hill Education.

[11] C.Y. Chang, W.H. Chen, L.H. Saw, A.A. Arpia, M.C. Uribe (2021). Performance analysis of a printed circuit heat exchanger with a novel mirror-symmetric channel design. Energies, 2021(14), 4252. https://doi.org/10.3390/en14144252

[12] Furmanov (2003). Temperature of steam in a turbine. https://hypertextbook.com/facts/2003/AlanFurmanov.shtml#:~:text= A%20steam%20turbine%20consists%20of,blades%2C%20which%20turns%20the%20axle.

[13] United States Environmental Protection Agency (2016). Technology. https://www3.epa.gov/otaq/gvg/learn-more-technology.htm

[14] Massachusetts Institute of Technology (n. d.) Printed-circuit heat exchangers (PCHE). https://ase.mit.edu/projects/printed-circuit-heat-exchanger-pche/

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