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ARTIFICIAL NEURAL NETWORK (ANN) BASED PREDICTION AND ANALYSIS OF VEHICLE EXHAUST WASTE HEAT RECOVERY POTENTIAL USING A RANKINE CYCLE

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Abstract—**This study of engine evaluates the vehicle exhaust WHR (waste heat recovery) potential using a Rankine cycle. To this end all the parts of the Rankine cycle used in the engine are designed by using a software, which is described further, basically, the thermodynamic analysis is performed for water R123 and R245fa and all the values of physical properties have been taken from a software. For talking the values from the software, we have connected two software (MATLAB 2019b and REFPRO 9.0) The effectiveness of heat exchanger for organic working fluid (R123 and R245fa) is higher than that of water and can be also considered for use in vehicle WHR applications through Rankine cycle when exhaust gas temperature is relatively low. The performance prediction and optimization of an organic Rankine cycle (ORC) for engine waste heat recovery based on artificial neural networks (ANN). An ANN-based prediction model of the ORC system is established with consideration of mean square error (MSE) and correlation coefficient(R). A concept of backpropagation is considered in this study which is the concept of ANN.we We have trained the data in a software that is explained further by importing the seven parameters with a limited number of input and two outputs for each parameter to the same software from excel. The proposed ANN model shows strong learning ability and good generalization performance. The results confirm the advantages of using the thermal energy contained in vehicle exhaust gases through RCs. Furthermore, the present analysis demonstrates that improved evaporator designs and appropriate expander devices allowing for higher evaporating pressures are required to obtain the maximum WHR potential from vehicle RC systems**.

Keywords: -ANN, REFPROP, WHR, Effectiveness, Backpropagation, ORC, correlation coefficient.

I. INTRODUCTION

Internal combustion engines are the major source of motive power in this world, and this is expected to continue for some decades.[1] Currently, internal combustion engines (ICEs) are still the main power for transportation. Energy conservation and emission reduction are two critical tasks for the ICE industry all over the world. Organic Rankine cycle (ORC) is a feasible technology to recover the waste heat of an ICE so that the energy efficiency can be enhanced apparently.[2] In recognition of the need to further reduce vehicle exhaust pollutant emissions (CO, NOx, hydrocarbons and particulate matter). Compared with other technologies such as improvements to combustion and friction, the utilization of waste heat has a greater potential for energy conservation and emission reduction. ORC technology is a method that can generate power from a low-temperature heat source such as the waste heat of the exhaust and the coolant of an ICE. For exhaust heat recovery, the working fluid of the ORC absorbs heat from the exhaust and outputs power via an expander. Hence the total power output and the energy efficiency of the ICEORC system are increased. The emissions of the ICE also decrease due to a reduction in fuel consumption. In ICEs, only about 1/3 rd of the fuel combustion energy is converted into useful work to drive the vehicle and its accessory loads.[3] The remainder is engine waste heat dissipated by the engine exhaust system and coolant system. Many parameters will influence the performance of an ORC. The selection of the organic working fluid is very important. selected an alkane as the working fluid and compared the performance indicators including the thermal efficiency, the work output, and the expander size parameters. To increase the ICEs thermal efficiency and to reduce CO2 emissions, different WHR (waste heat recovery) techniques were recently proposed. Among the existing WHR techniques, the most important are the ETC (electrical turbo-compounding), the MTC (mechanical turbocompounding), the TIGERS (turbo-generator integrated gas energy recovery system), the TEG (thermoelectric generator) and the RC (Rankine cycle) The results indicated that the ORC was superior to the steam cycle and the converting efficiency from low-grade waste heat to useful energy was higher.[4] The performances of different working fluids in specific operation regions by using the thermodynamic model built by MATLAB and REFPROP9.0 are analysed. The first studies and applications of the engine-ORC compound were specific for heavy-duty vehicles and arose during the energy crisis in the 1970s. In 1976, Patel and Doyle developed the first application for exploiting an ORC for the automotive engine, using the exhaust waste heat of a Mack 676 Diesel engine installed in a long-haul truck duty cycle. The constructed prototype showed an improvement in fuel economy of 12.5%. Heywood in 1981 proposed a review of the possible alternative systems be coupled to "Modelling and Optimization of Organic Rankine Cycle for Waste Heat Recovery in Automotive Engines," among them the ORC plant showed that a reduction of fuel consumption by 10-15 % could be reached on Diesel engines.[5] Several studies were carried out on ORC systems in the following years, among these assume relevance the comparison of the performance of different cycles applied to a Diesel engine, the design of the ORC control system and the comparison among seven working fluids. The effective interest of the automotive industry towards the waste heat recovery via ORC was neglected during the 90s in their analyses of the state of art. [6] The heat transfer model permits to perform heat exchanger sizing calculations and to assess the different heat exchanger efficiencies and pressure drop. Finally, both the thermodynamic RC and the heat exchanger models were used together to evaluate the vehicle exhaust WHR potential using different RCs. The evaporator and the expander are the 2 most critical components of an RC system. The present study considers available components (evaporator and expander) that allow building a short-term RC prototype for WHR in-vehicle applications.[7]

II. RANKINE CYCLE MODEL

A Rankine cycle is a closed-cycle system where a working fluid circulates through a minimum of an evaporator, turbine, condenser and a pump to convert heat into work. The evaporator can incorporate or be followed by a superheater if the working fluid/heat source temperature allows it. The conventional working fluid for Rankine cycle plants is water.[8] In a subcritical Rankine cycle, the temperature and pressure of the working fluid remain below the critical temperature and pressure. In a supercritical Rankine cycle, the fluid pressure is raised above the critical pressure and heat addition continues until the critical temperature is exceeded; heat rejection remains subcritical. Supercritical operation avoids the iso-thermal portion of the heat addition of the subcritical cycle, thus raising the average temperature during heat addition and reducing the irreversibility of the heat transfer process. Supercritical Rankine cycles are sometimes referred to as trans critical cycles. Because heat rejection in a Rankine cycle is via condensation from a gas to a liquid, heat rejection returns the working fluid to a subcritical state.[9]

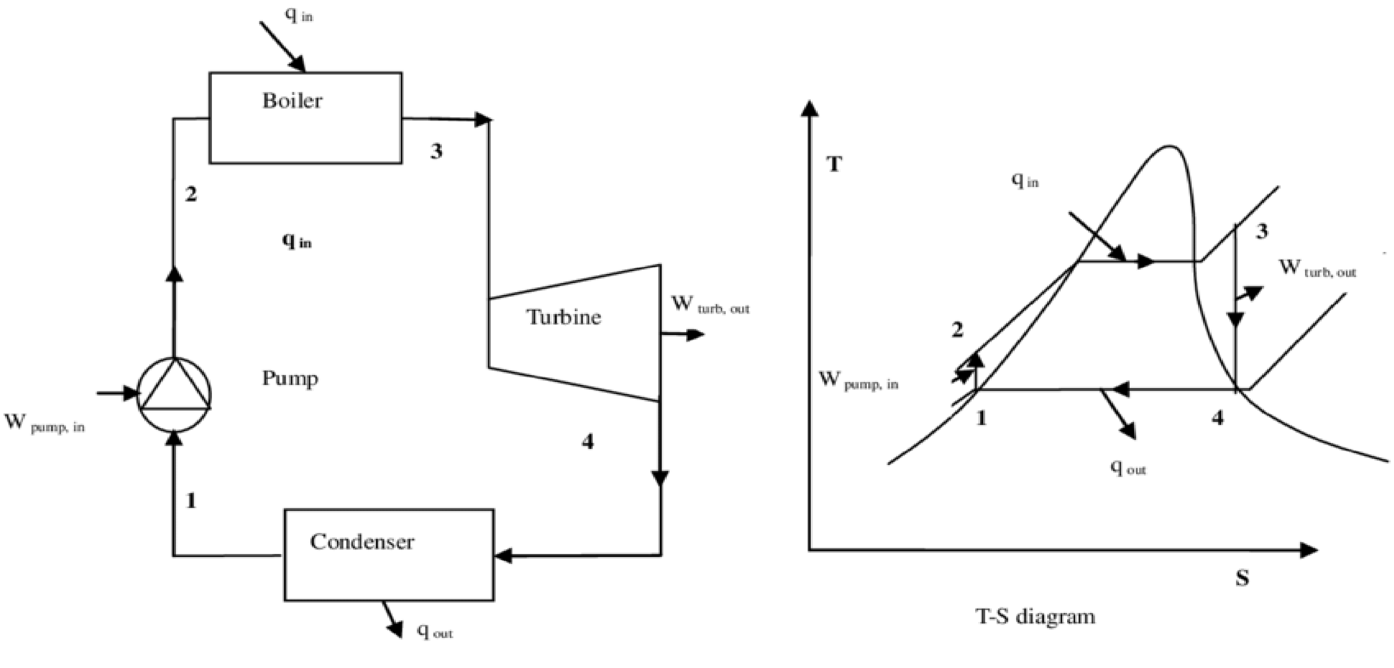

Fig. 1. Rankine cycle model

II.A. There are four processes in the Rankine cycle: -

PROCESS 1–2**(**Isentropic compression**)**-The working fluid is pumped from low to high pressure. As the fluid is a liquid at this stage, the pump requires little input energy.

PROCESS 2–3**(**Constant pressure heat addition**)**-The high-pressure liquid enters the evaporator, where it is heated at constant pressure by an external heat source to become a dry saturated vapor.

PROCESS 3–4**(**Isentropic expansion**)**-The dry saturated vapor expands through a turbine, generating power. This decreases the temperature and pressure of the vapor, and some condensation may occur.

PROCESS 4–1**(**Constant pressure heat rejection**)**-The wet vapor then enters a condenser, where it is condensed at a constant pressure to become a saturated liquid

III. HEAT EXCHANGER MODEL

The waste heat of the exhaust gas was transferred to the working fluid inside the evaporator. A shell-and-tube heat exchanger was employed in this study. The main parameters are (Tube length, Tube diameter, Tube number, Shell diameter, Path number). The heat transfer process inside the evaporator can be divided into three zones: The liquid zone, the two-phase zone, and the gaseous zone. For the single-phase zone, the convective heat transfer of the working fluid was determined by the Dittus-Boelter equation:[11]

$$h = 0.023 Re^{0.8} Pr^{0.4} \frac{K}{D}$$

where h is the convective heat transfer coefficient (W/m2 ·K), Re is the Reynolds number, Pr is the Prandtl number, K is the thermal conductivity (W/m·K), and D is the characteristic length.[12]

The heat exchanger (evaporator) is an essential component in vehicle WHR applications. The following characteristics are desirable in a heat exchanger for such applications:

- high heat exchanger effectiveness;
- low-pressure drop through the heat exchanger, which minimizes the negative impact of the exhaust back pressure on the ICE;
- compactness. Improvements in the heat exchanger effectiveness can be obtained by increasing the heat transfer area or the heat transfer [13,3]

The **Number of Transfer Units (NTU) Method** is used to calculate the rate of heat transfer in heat exchangers (especially counter current exchangers) when there is insufficient information to calculate the Log-Mean Temperature Difference (LMTD). In heat exchanger analysis, if the fluid inlet and outlet temperatures are specified or can be determined by simple energy balance, the LMTD method can be used; but when these temperatures are not available The NTU or The Effectiveness method is used.[14]

To define the effectiveness of a heat exchanger we need to find the maximum possible heat transfer that can be hypothetically achieved in a counter-flow heat exchanger of infinite length. Therefore one fluid will experience the maximum possible temperature difference, which is the difference of T_{hi}-T_{ci} (The temperature difference between the inlet temperature of the hot stream and the inlet temperature of the cold stream). The method proceeds by calculating the heat capacity rates (i.e. mass flow rate multiplied by specific heat) C_h and C_C for the hot and cold fluids respectively, and denoting the smaller one as $C_{min...}$

A problem encountered in heat exchanger analysis is the determination of the heat transfer rate and the outlet temperatures of the hot and cold fluids for prescribed fluid mass flow rates and inlet temperatures when the type and size of the heat exchanger are specified. In such situations, we use the NTU-Effectiveness method (NTU: Number of Transfer Units = Non-dimensional parameter).[15]

Heat transfer effectiveness

$$(€) = \frac{Actual\ heat\ transfer\ rate}{maximum\ possible\ heat\ transfer\ rate}\frac{}{max}$$

- The effectiveness of a heat exchanger depends on the geometry of the heat exchanger as well as the flow arrangement.
- Therefore, different types of heat exchangers have different effectiveness relations.
- We illustrate the development of the effectiveness relation for the double-pipe parallel-flow heat exchanger.

The heat exchanger was divided into three zones for modelling purposes, a preheating zone, an evaporating zone, and a superheating zone. These zones were considered individual heat exchangers with the appropriate boundary conditions for temperature and mass flow rate. The amounts of exchanged heat for preheating, evaporating and superheating of the RC working fluid were estimated from the heat transfer relations and the ε-NTU method. We have designed the heat exchanger model, which was also implemented in MATLAB SIMULINK. The required thermodynamic and transport properties for the exhaust gases were calculated with the aid of the REFPROP 9.0. The calculations were performed for different evaporating pressures and working fluids until reaching convergence between the working fluid mass flows in the various sub-components of the heat exchanger.

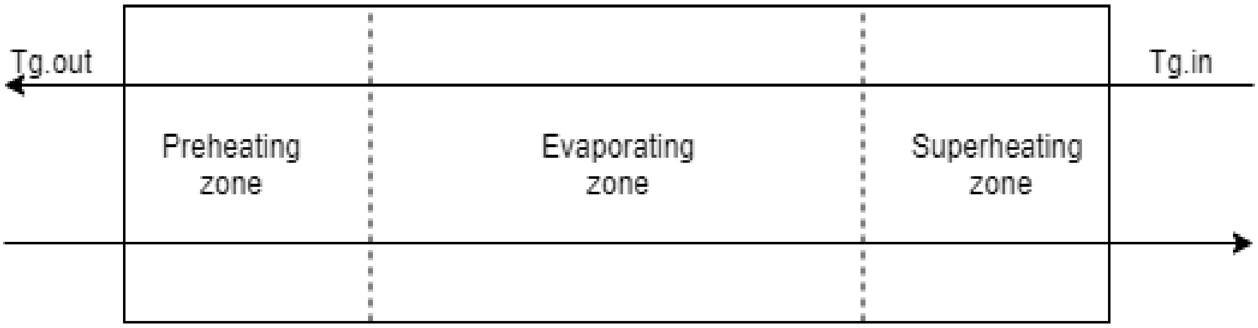

Fig. 2 The three zones of the heat exchanger considered for modelling purpose.

IV. PUMP

A pump is a device that moves fluids (liquids or gases), or sometimes slurries, by mechanical action. Pumps can be classified into three major groups according to the method they use to move the fluid: direct lift, displacement, and gravity pumps. Pumps operate by some mechanism (typically reciprocating or rotary) and consume energy to perform mechanical work moving the fluid. Pumps operate via many energy sources, including manual operation, electricity, engines, or wind power [16]

We have chosen centrifugal pump for Rankine cycle model as it had advantages over another pump. A centrifugal pump is a mechanical device designed to move a fluid utilizing the transfer of rotational energy from one or more driven rotors, called impellers. Fluid enters the rapidly rotating impeller along its axis and is cast out by centrifugal force along its circumference through the impeller's vane tips. The action of the impeller increases the fluid's velocity and pressure and also directs it towards the pump outlet. The pump casing is specially designed to constrict the fluid from the pump inlet, direct it into the impeller and then slow and control the fluid before discharge.[17]

IV.A. WORKING

The first step in the operation of a centrifugal pump is priming. Priming is the operation in which suction pipe casing of the pump and the position of fluid with the liquid which is to be pumped so that all the air from the position of pump is driven out and no air is left. The necessity of priming of a centrifugal pump is because the pressure generated at the centrifugal pump impeller is directly proportional to density of fluid that is in contact with it.[18]. After the pump is primed the delivery valve is still kept closed and electric motor is started to rotate the impeller. The delivery valve is kept closed in order to reduce valve is opened the liquid is made to flow in an outward radial direction there by vanes of impeller at the outer circumference with high velocity at outer circumference due to centrifugal action vacuum is created. This cause liquid from sump to rush through a suction pipe to eye of impeller thereby replacing long discharge from centre circumference of the impeller is utilized in lifting liquid to required height through delivery pipe.[18]

IV.B. ADVANTAGES

- Pump A multistage centrifugal pump is selected as a working fluid pump owing to its advantages of stable operation, low vibration, long lifetime and high efficiency.
- Installation and maintenance are easier and cheaper as compared to reciprocating pump
- Centrifugal pump has much greater discharging capacity than reciprocating pump
- Centrifugal pump is compact and small in size and have less weight for the same capacity and energy transfer as compared to reciprocating pump.[19]
- It can handle all types of fluids and can be mounted horizontally or vertically both.

IV.C. We have generated function of centrifugal pump in MATLAB SIMULINK by incorporating the values of all physical properties from REFPROP 9.0.

```
function [Wd,Emech,Teff,Hs,Eman,U,Re,Hm,Hf,NSPH]=PUMP(D,N,W,nu,hs,hd,sp,V,Patm,L)

rho=refpropm('D','T',296,'P',100,'WATER');

Re=rho*V*D/nu;
if Re<2100

    f=64/Re;
else
```

```
    f=0.374/Re;
end
Hf=4*f*L*V^2/2*9.81*D;


U=3.14*D*N/60;

Hs=hs+hd;

Vw=V*cos(3.14/2);

Wd=Vw*U/9.81;

Vd=V^2/2*9.81;

Hm=Wd-(Hf+Vd);

Eman=Hm/Wd;

Emech=W*Wd/1000*sp;

Teff=Eman*Emech;

Pvap=refpropm('P','T',373.15,'Q',0,'water');

NSPH=Patm/rho*9.81-Pvap/rho*9.81-Hf-hs;
```

W_d	work done	D	diameter of inlet.
E_{mech}	Mechanical efficiency	N	Speed
T_{eff}	Total efficiency	W	Total weight
Hs	Static head	nu	fluid dynamic viscosity
Eman	Manometric efficiency	hs	Suction head
U	Tangential velocity of impeller.	hd	Delivery head
Hf	Friction losS	sp	Shaft power
NSPH	Net positive suction head	V	Velocity of flow
Patm	Atmospheric pressure	L	Length of the pipe.
Hm	-actual delivery height.	rho	Density of fluid
f	Friction factor	Vw	Whirl velocity of fluid
Vd	Velocity head	Pvap	Vapour pressure

Table. 1

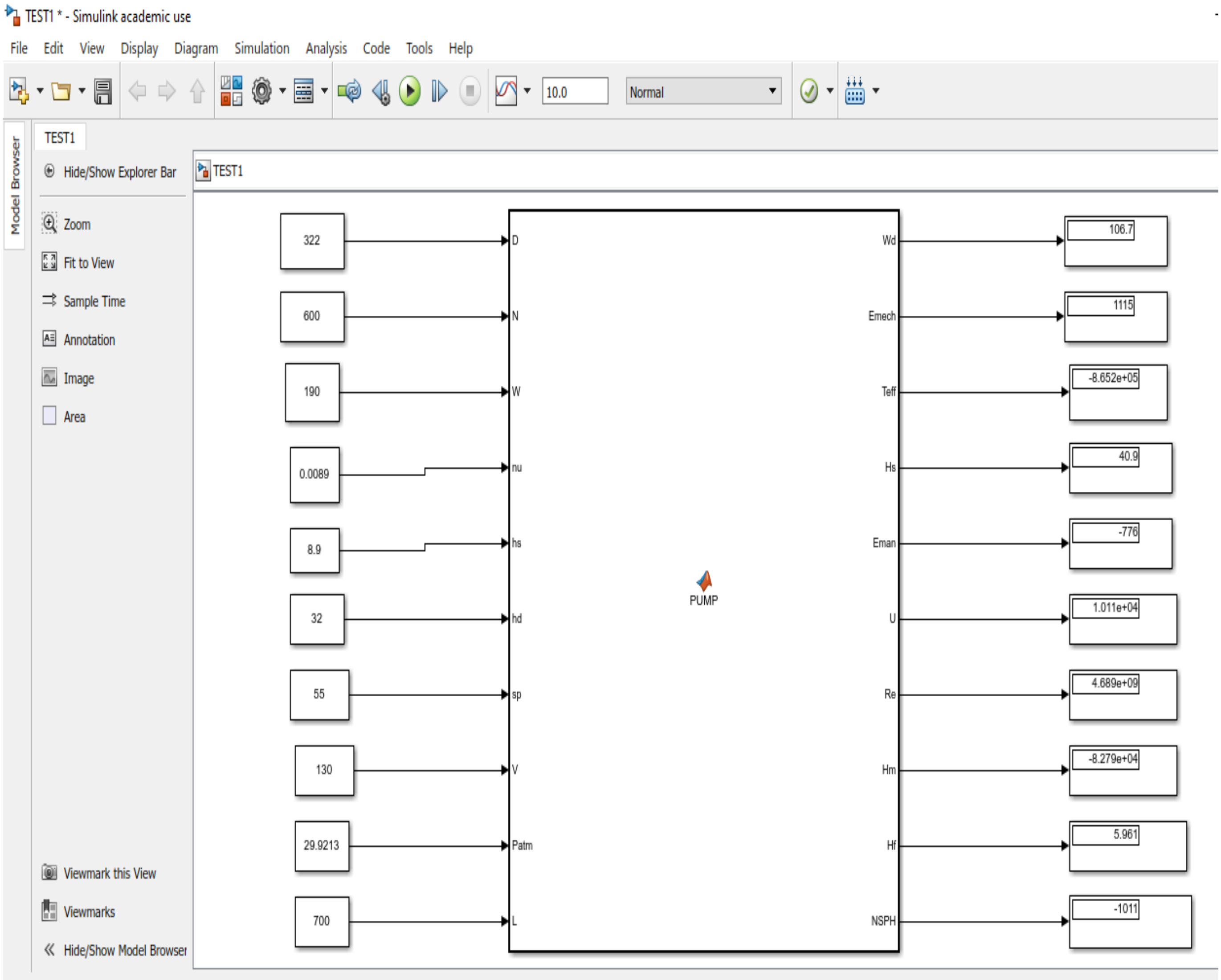

Fig.3.functions of pump.

V. CONDENSER

a condenser is a device or unit used to condense a gaseous substance into a liquid state through cooling. In so doing, the latent heat is released by the substance and transferred to the surrounding environment. Condensers are used for efficient heat rejection in many industrial systems. Condensers can be made according to numerous designs [20]. A condenser is designed to transfer heat from a working fluid (e.g. water in a steam power plant) to a secondary fluid or the surrounding air. The condenser relies on the efficient heat transfer that occurs during phase changes, in this case during the condensation of vapor into a liquid. The vapor typically enters the condenser at a temperature above that of the secondary fluid. As the vapor cools, it reaches the saturation temperature, condenses into liquid and releases large quantities of latent heat. As this process occurs along with the condenser, the quantity of vapor decreases and the quantity of liquid increases; at the outlet of the condenser, only liquid remains. Some condenser designs contain an additional length to sub cool this condensed liquid below the saturation temperature.[21]

Condensers have two significant design advantages over other cooling technologies:

- Heat transfer by latent heat is much more efficient than heat transfer by sensible heat only
- The temperature of the working fluid stays relatively constant during condensation, which maximizes the temperature difference between the working and secondary fluid.

For an ideal single-pass condenser whose coolant has constant density, constant heat capacity, linear enthalpy over the temperature range, perfect cross-sectional heat transfer, and zero longitudinal heat transfer, and whose tubing has constant perimeter, constant thickness, and constant heat conductivity, and whose condensable fluid is perfectly mixed and at constant temperature, the coolant temperature varies along its tube according to:

$$\theta(x) = \frac{TH - T(x)}{TH - T\,(0)} = e^{-NTU} = e^{-\frac{hpx}{mc}} = e^{-\frac{Gx}{mcL}}$$

where:

- x is the distance from the coolant inlet;
- T(x) is the coolant temperature, and T (0) the coolant temperature at its inlet;
- T_H is the hot fluid's temperature;
- NTU is the number of transfer units;
- m is the coolant's mass (or other) flow rate;
- c is the coolant's heat capacity at constant pressure per unit mass (or other);
- h is the heat transfer coefficient of the coolant tube;
- P is the perimeter of the coolant tube;
- G is the heat conductance of the coolant tube (often denoted UA);
- L is the length of the coolant tube.

At the condenser, the exergy destruction rate expresses the sum of the irreversibility of the condenser and the exergy discharged with the cooling air that flows across the condenser. Apart from the simple RC, other RC configurations permit to increase the recovered thermal energy. For example, the thermal efficiency of a RC can be augmented by adding a preheater or a regenerator. To improve heat transfer performance, people usually roughen the surface of heat transfer tubes to increase the area for enhancement of heat transfer characteristics. Such tubes are called enhanced heat transfer tubes or enhanced tubes. Enhanced tubes are widely used in industry to make shell and tube heat exchangers, due to their superior heat transfer performance. However, fouling of heat transfer surfaces is a serious problem that affects the design and operation of heat exchangers. Considering the influence of fouling, the heat transfer surface area is usually designed to be oversized by an average of 35% [22]. Fouling involves the accumulation of undesired deposits with low thermal conductivity on heat transfer surfaces, leading to the degradation of heat transfer and hydraulic performance of the equipment. Six mechanisms are contributing to water-side fouling: particulate, precipitation, chemical reaction, corrosion, bio-fouling, and freezing fouling [2]. Of them, precipitation fouling was the main component of waste side fouling [23].

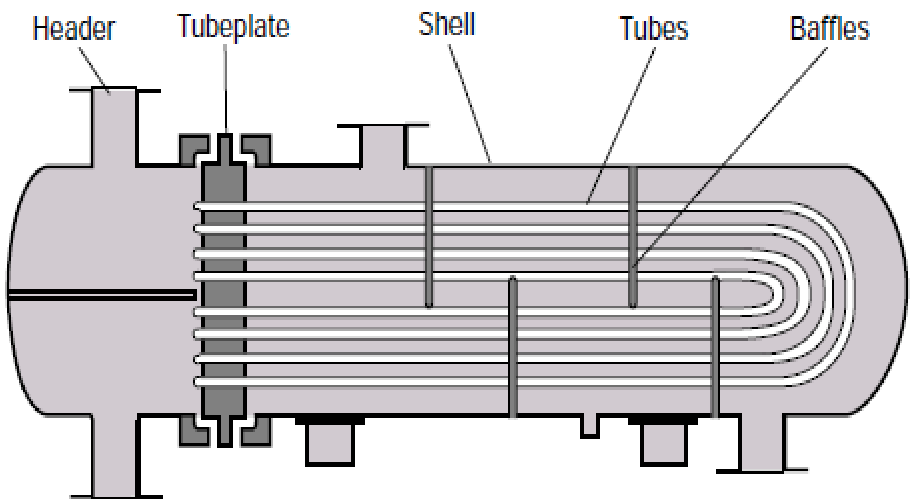

Fig. 4. condenser parts

V.A.We have generated function of shell and tube condenser in MATLAB SIMULINK by incorporating the values of all physical properties from REFPROP 9.0.

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```
function [Ae, mf, V, De, Re, Pd, LMTD, Ua] =condenser (Ds,Dto,Dti, P,Bs,Q,To,Ti,nu,hs,ha,N)

Ae=Ds*Bs*(P-Dto)/P;

rho=refpropm('D','T',323.15,'P',5.5,'WATER'); //incorporating value from REFPROP 9.0

cp=refpropm('C','T',323.15,'P',5.5,'WATER');   //incorporating value from REFPROP 9.0

mf=Q/cp*(To-Ti);

V=mf/(rho*Ae*3600);

De=4*(P^2-(3.14*(Dto)^2/4)/3.14*Dto);

Re=rho*V*Dto/nu;                              //for deciding type of flow of fluid
                                                    (laminar or turbulent)
if Re<2100

   fk=64/Re;

else

   fk=0.374/Re;

end

Pd=((N+1) *fk*Ds*rho*V^2)/(2*De);

LMTD=To-Ti/log (To/Ti);

K=refpropm('L','T',323.15,'P',4.8,'WATER');          //incorporating value from REFPROP 9.0

Ua=1/((0.5*Dto)/hs*(0.5*Dti)+1/ha+(0.5*Dto)*log((0.5*Dto)/(0.5*Dti))/K);
```

Ae	Effective area	Ds	Shell diameter
mf	Mass flow rate	Dti	Tube inner diameter
V	Velocity of crossflow	Dto	Tube outer diameter
Re	Effective diameter	P	Pitch (distance b/w center axes of two adjacent tubes)
Pd	Pressure drop	Bs	Baffle diameter
LMTD	Logarithmic mean temperature difference	Q	Flow rate
UA	Heat transfer coefficient	To	Outlet temperature
Ti	Inlet temperature	Ha	Heat transfer coefficient on airside
nu	Dynamic viscosity of fluid	fk	Friction factor
hs	Heat transfer coefficient on steam side	N	Tube length

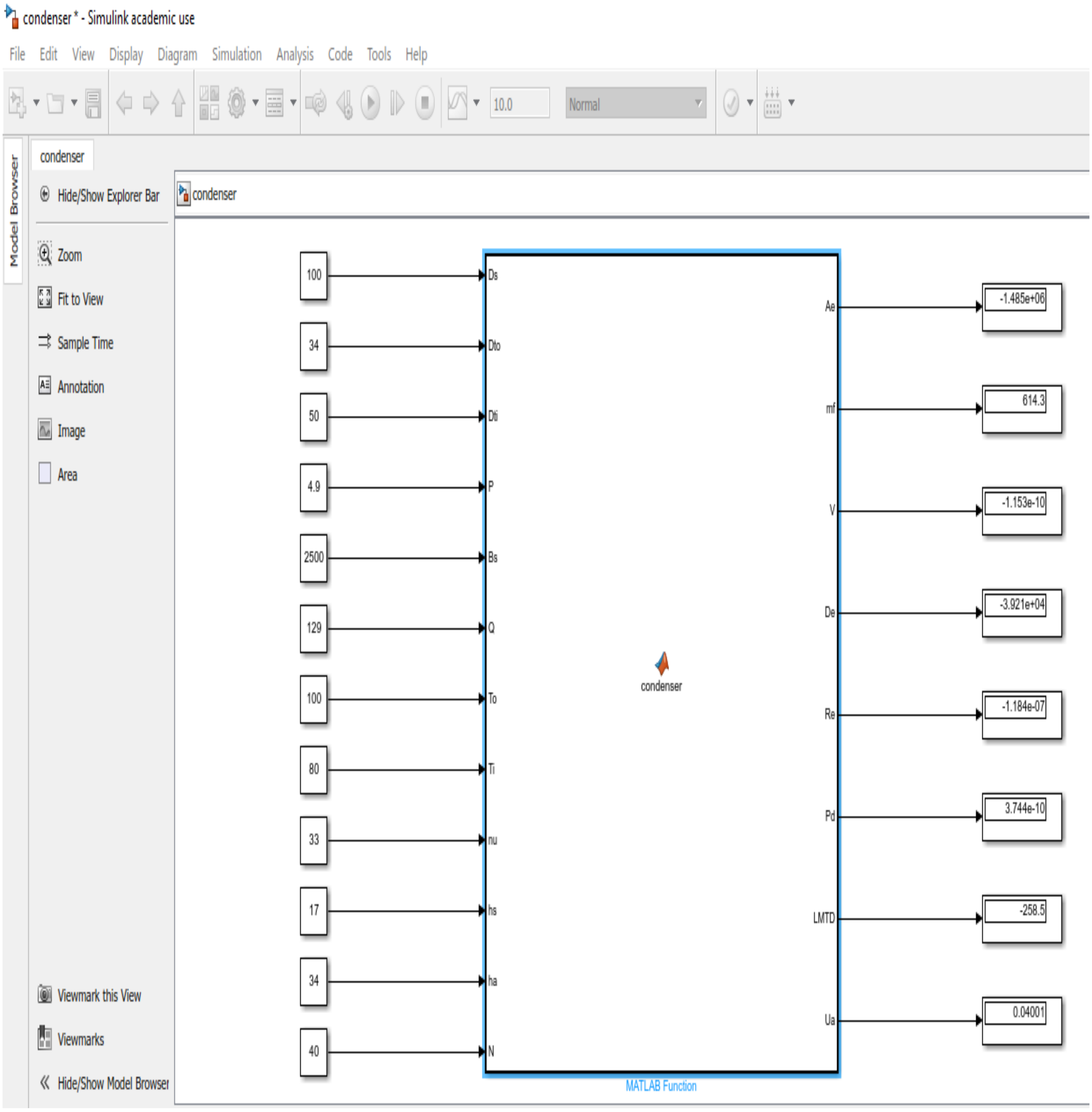

Fig.5.function of condenser

VI. TRAINING OF DATA (INPUT AND OUTPUT) BY ARTIFICIAL NEURAL NETWORK IN MATLAB.

An artificial neural network is a computing model, which is composed of a collection of artificial neurons. Each artificial neuron represents a particular output function called activation function, while each We have taken seven input parameter numbers of inputs and trained the data in MATLAB Neural network for getting efficient work output. the connection between two neurons has a weight that represents the memory of an ANN model. ANN method can be used to deal with highly nonlinear, non-limitation and non-convexity systems.[24]

V	Volume (L/min)
Pi	Expander inlet pressure (bar)
Po	Expander outlet pressure (bar)
Ti	Expander inlet temperature (°c)
To	Expander outlet temperature (°c)
Pp	Pump outlet pressure (bar)
Tor	Expander torque (Nm)
Wexp	Expander power (Kw)

Table 2

```
V=15:0.033:25;

Pi=8:0.0133:12;

Po=1.4:0.0086:4;

Ti=105:0.116:140;

To=40:0.033:50;

Pp=7:0.0066:9;

Tor=20:0.116:55;

disp(V, Pi,Po,Ti,To,Pp,Tor);
```

The reasons for selecting the above mentioned seven operating parameters are- When operating condition of the diesel engine is determined, volume flow rate and expander torque can be regulated. Working fluid flow rate is the only parameter that we can control to change other operating parameters in an actual ORC system. Expander inlet and outlet pressures determine the expansion ratio affecting the final power output. Superheat degree is also closely related to the expander inlet temperature and pressure. Besides, lowering condenser outlet temperature is beneficial to improve the thermal efficiency of the ORC system. Circulating the water flow rate of the cooling tower or operation frequency of the air-cooled heat exchanger needs to be regulated based on the condenser outlet temperature. Furthermore, pump outlet pressure affects the operation pressure of the whole ORC system. A single hidden layer BP (backpropagation) neural network is considered to simplify the computation.

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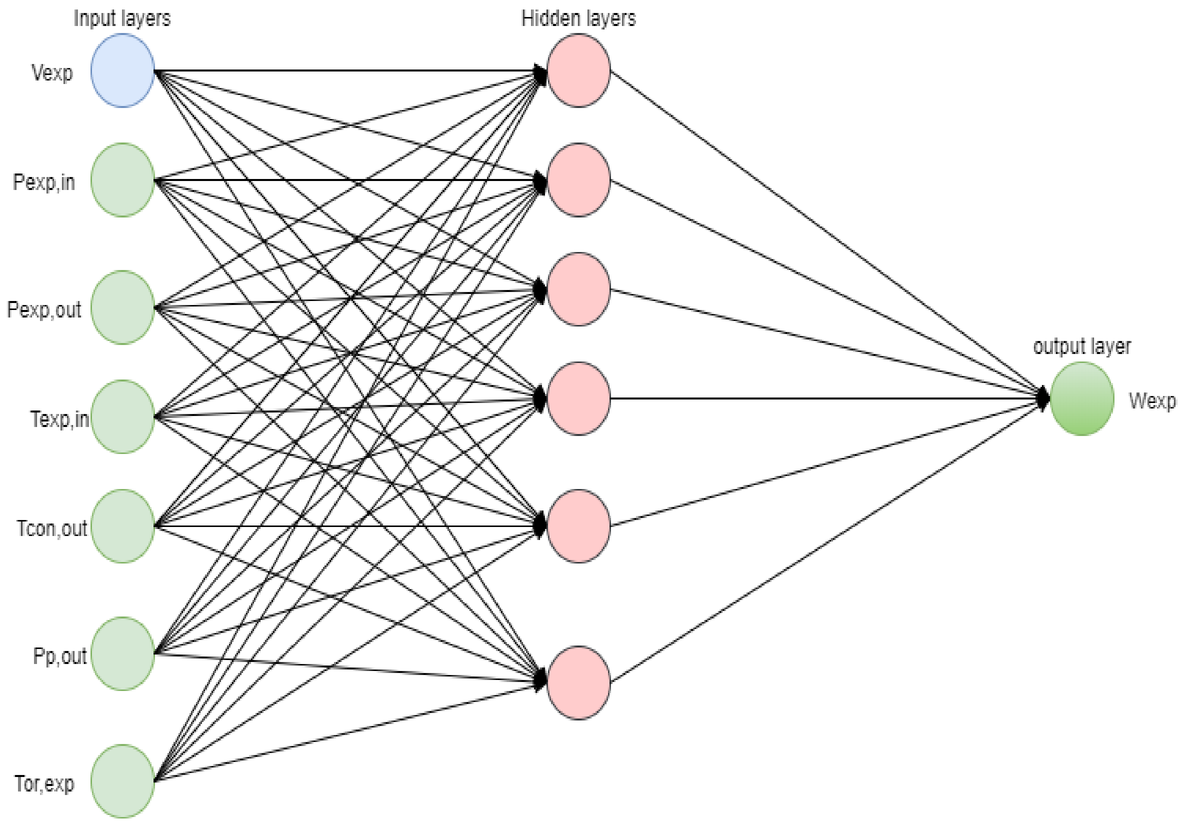

Fig.6. Topology chart of parameters.

To evaluate the prediction performance of the ANN model, two common metrics are used in this work. The first one is mean squared error (MSE), The simplest and most commonly used error function in neural networks used for regression is the mean square error (MSE) which is a convenient method to measure the average change in data. Generally, a low MSE value represents a high-accuracy prediction., the ANN model is evaluated first under different learning rates, train functions. A. The learning rate is used to adjust the weights and biases of an ANN model. A high learning rate can result in oscillation and instability, while a low learning rate leads to a long convergence time.

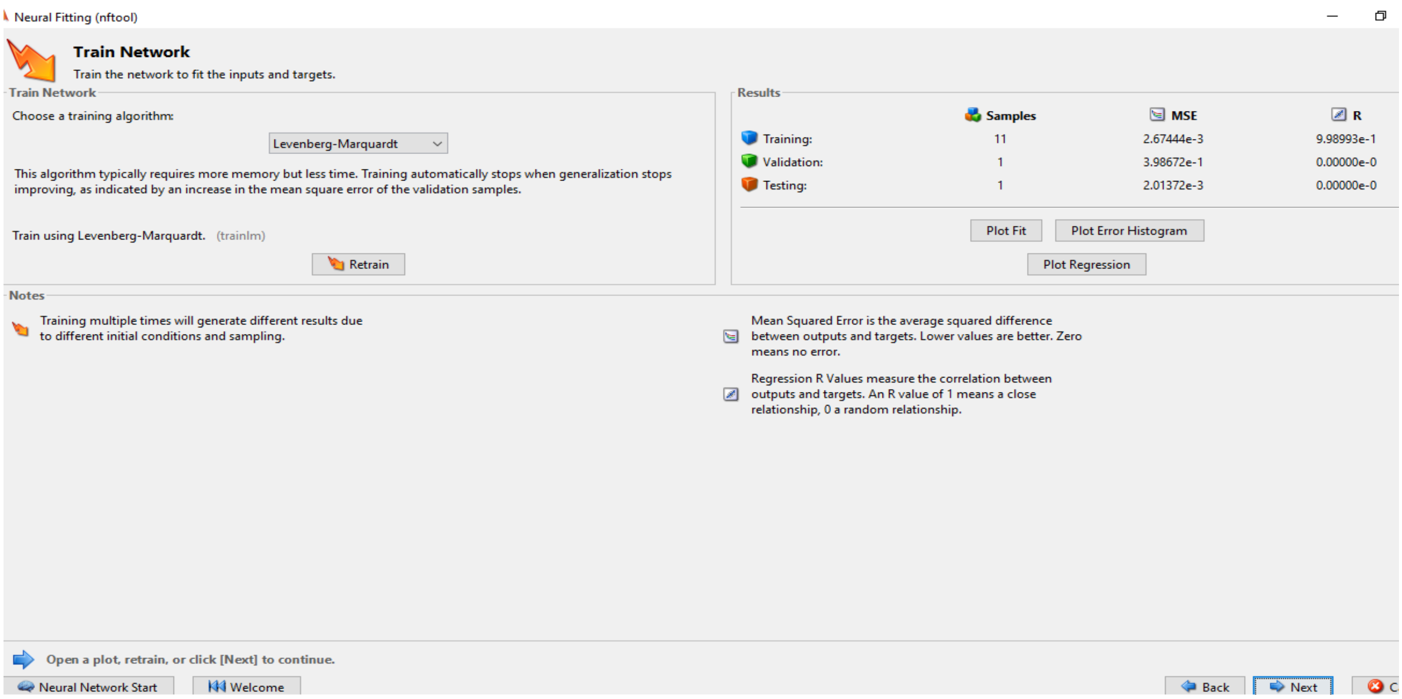

Fig.7.Training algorithm and comparison between MSE and R

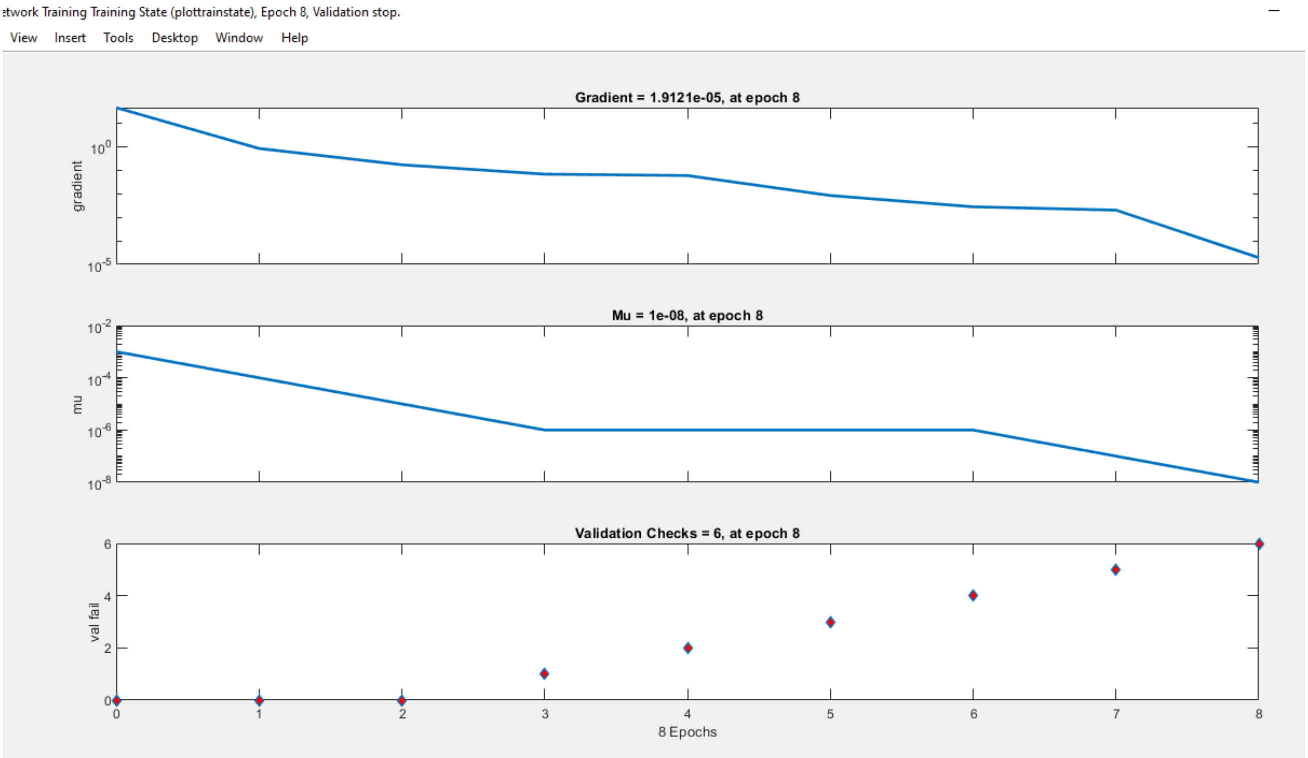

Fig.8.Neural network training state

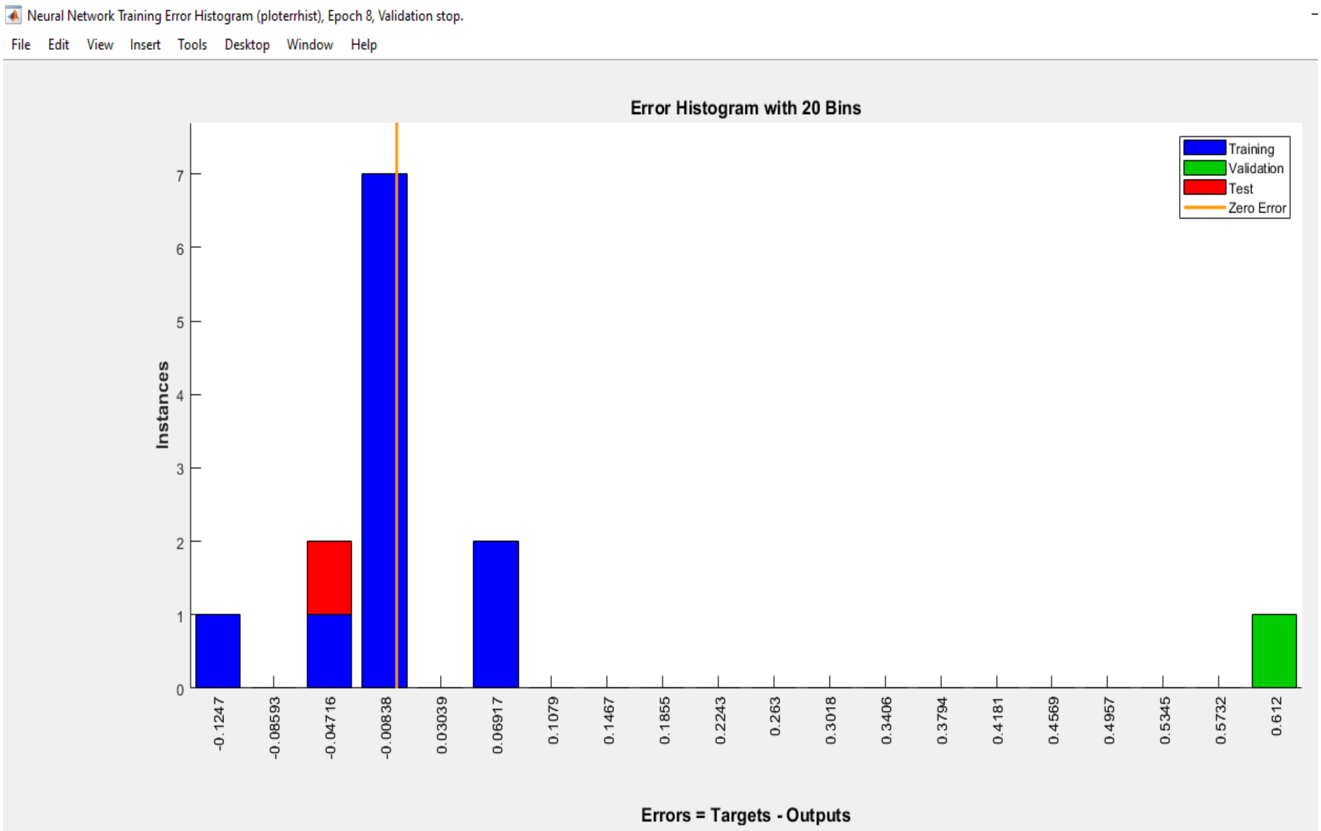

Fig.9.Error histogram

VII. CONCLUSION

Organic Rankine Cycle (ORC) can convert low medium grade heat into electrical or mechanical power and has been widely recognized as the most promising heat-driven technologies. A typical internal combustion engine (ICE) converts around 30% of the overall fuel energy into effective mechanical power and the rest of fuel energy is dumped through the engine exhaust system and cooling system. Integrating a well-designed ORC system to ICE can effectively improve the overall energy efficiency and reduce emissions with around 2–5 years of payback period through fuel saving. By using artificial neural network(ANN), we have optimized the parameters that we have selected for the organic Rankine cycle for the recovery of waste heat engine.as we have used the backpropagation method in ANN by this we have selected an output for making it most efficient at the particular values of parameters, we have trained the data in, MATLAB by importing the data from excel after which we got the output values till some extent

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