A PC Based Diesel Engine Simulation Program For Marine Engineers.

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Abstract This paper describes a PC based Diesel Engine Cycle SIMulation (DECSIM) program that was developed at the Australian Maritime College. DECSIM has been validated against a variety of marine engines and can be used to predict the steady state performance characteristics of two and four stroke diesel engines. The program may be used to obtain pressure-crank angle, pressure-volume and heat release diagrams. Applications of DECSIM are discussed that show how the program can be used to assist marine engineers in fault diagnosing and designers to predict the thermal behaviour of combustion chamber components. The program may also be used to model cooling system behaviour and so can be used by design engineers to optimise the dimensions of components such as heat exchangers and pumps with acceptable system pressure drop characteristics.

1. INTRODUCTION

Diesel engine simulation in use at the Australian Maritime College may be classified into two main areas, real time simulation and engine cycle simulation. The diesel engine training simulator described by Pal (1991) is an example of how a real time simulator is used at the College to impart operational and diagnostic fault finding skills to aspiring marine engineers. This simulator replicates the main machinery plant of a 120,000 tonne Bulk Carrier including the main propulsion plant, which is a seven cylinder Mitsubishi two stroke, slow speed engine. It is comprised of a simulated ship's engine room, control room, separate instructor's room and mini computer. Students are trained for normal engine room operations, such as preparing the plant for departure and arrival in port, as well as emergency situations such as a total loss of electrical power and crash astern manoeuvres. An important requirement for such a simulator is that it should faithfully model the machinery's response behaviour in real time. Engine cycle simulation programs on the other hand, may take several hours of computing time to model an engine's transient response behaviour that may last only several seconds in real time. These programs can be used to predict the performance of a variety of engines, including exhaust emissions, over a wide range of operating variables. Engine cycle simulation programs are widely used by engine manufacturers to provide information for the detail design of current and future engines .

The DECSIM (Diesel Engine Cycle SIMulation) program described in this paper is a modified version of a program created by Colthorpe (1991) to run on a 386 PC computer. The original program was developed for use by students taking the Power Plant Theory elective in the BEng (Maritime) Degree at the College. It was a DOS based program that permitted students, using a minimum of input data, to investigate the effects on an engine's performance of changing values for engine bore, stroke, injection timing, and valve opening and closing angles. The value of a simple to use, steady state engine cycle program in the engine thermal analysis work being undertaken at the College was recognised and the program which became known as DECSIM, has been modified and improved over a period of years. The latest additions are cooling system modelling capabilities and the development by Martin (1996) of a windows based graphical user interface.

2 DESCRIPTION OF THE SIMULATION MODEL

2.1 Engine System Model

DECSIM is a thermodynamic model based on the step-by-step 'emptying and filling' method described by Watson and Janota (1982). The conservation equations are used to evaluate the work, heat and mass transfer taking place across the boundaries of the control volume. A constant manifold pressure is assumed, and the mass transfer rate across valves and ports are calculated using the orifice analogy. For subsonic flow this is described by:

$$\dot{m} = Cd.A.P_u \sqrt{\left(\frac{2\gamma}{\gamma - 1}\right)\left(\frac{1}{R_u.T_u}\right)\left[\left(\frac{P_d}{P_u}\right)^{\frac{2}{\gamma}} - \left(\frac{P_d}{P_u}\right)^{\frac{\gamma+1}{\gamma}}\right]} \qquad (1)$$

and for choked flow

$$\dot{m} = Cd.A.P_u \sqrt{\left(\frac{\gamma}{R_u.T_u}\right)\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma+1}{\gamma-1}}} \qquad (2)$$

where $\dot{m}$ is the mass flow rate through the valve or port, Cd is the discharge coefficient, A is the area, γ, R, T and P refer to the specific heat ratios, the specific gas constant, temperature and pressure respectively for the fluid. The subscripts d and u denote downstream and upstream respectively.

During the scavenging period for two stroke engines, a single zone non-isothermal perfect mixing model, as described in Benson and Whitehouse (1979) is used. In this model, it is assumed that the fresh charge air mixes instantaneously with the cylinder contents to form a homogeneous mixture. The instantaneous composition of the gas leaving the cylinder through the exhaust port, is therefore a mixture of fresh charge air and burnt gas at the same mixing ratio.

Mechanical losses from friction are obtained using the Millington and Hartles (1968) equation which describes motoring losses in terms of compression ratio, piston speed and crankshaft speed.

2.2 Combustion Model

The heat released during combustion of the fuel is calculated by DECSIM using the Whitehouse and Way method as detailed in Benson and Whitehouse (1979). This semi empirical formula for calculating the rate of combustion is based on the rate of fuel injection and the amount of oxygen available in the cylinder. This model treats the combustion rate as being comprised of two parts: a preparation limited combustion rate and a reaction limited combustion rate. The rate of fuel preparation is given by the following equation:

$$P_f = k_p M_i^{1-x} M_p^{x} Po_2^{d} \tag{3}$$

where P_f is the preparation rate at which injected fuel is made ready for combustion by evaporation and mixing with oxygen. It is proportional to the mass of fuel injected but not yet prepared (M_i -M_p) and the partial pressure of oxygen Po_2. The terms k_p, x, and d are constants controlling the preparation rate. The terms M_i and M_p represent the mass of fuel injected and the cumulative mass of fuel prepared. During premixed combustion, the fuel burning rate is controlled by chemical kinetics and is calculated as follows:

$$R_f = \frac{k_R \, Po_2 \, e^{-\frac{act}{T}}}{N\sqrt{T}}\left(P_n - R_{n-1}\right) \tag{4}$$

where R_f is the reaction rate at which the prepared fuel is burnt during the premixed phase of combustion, k_R and act are empirical constants controlling the reaction rate. The average temperature in the cylinder during the current step is T (K) and N is the revolutions per second of the engine. P_n is the total fuel prepared to the current step and R_{n-1} is the total fuel burnt up to the current step. At the start of combustion, the fuel burning rate is less than the preparation rate, which results in the accumulation of the prepared fuel. This fuel accumulation causes an increase in the burning rate, which causes a peak in the heat release rate. After the prepared fuel is exhausted, the rate of heat release is equal to the rate of fuel preparation.

Typical values for k_p , k_R , d, and act are given in Benson and Whitehouse for four small bore diesel engines and Goldsworthy (1987) suggests the following values can be used for a Mitsubishi slow speed two stroke diesel engine.

$k_p = 0.02$ $\quad d = 0.5$ $\quad k_R = 7.0 \times 10^5$ $\quad act = 1\times10^4$

2.3 Heat Transfer Model

DECSIM uses a one-dimensional heat flux model to describe the heat transfer through the wall into the coolant. Heat fluxes through the piston, cylinder liner and cylinder head are calculated separately based on a resistance network analogy approach. The heat flow path between the cylinder gases and the engine coolant can be considered to consist of three parts; gas to wall, conduction through wall, and wall to coolant. In the model a composite wall is used with the option of using up to three layers with different thickness and material properties. Wall to coolant convection heat transfer is modelled using empirical bulk surface heat transfer coefficients. Heat transfer between the cylinder gases and the wall is calculated using Annand's equation as quoted in Benson and Whitehouse (1979).

$$\frac{dQ}{dt} = A_w\left[ak\frac{\mathrm{Re}^b}{D}\left(T - T_w\right) + c\left(T^4 - T_w^4\right)\right] \tag{5}$$

where Re = Reynolds Number $= \dfrac{\rho \, DV_p}{\mu}$

D is the cylinder bore, A_w is the exposed cylinder wall area and Vp is the piston velocity. T refers to the average cylinder instantaneous gas temperature and T_w the cylinder wall temperature while a, b, and c are constants. The fluid property terms, μ, ρ and k refer to the cylinder gas viscosity, density and thermal conductivity respectively.

Annand's equation is used because it includes the effects of radiation heat transfer. Radiation heat transfer has been found to have a more significant effect in diesel engines than in spark-ignition engines. The mean effective heat transfer coefficient for two stroke engines is calculated as

$$\bar{h} = \frac{1}{360}\int_0^{360} h.d\theta \tag{6}$$

where h is the instantaneous heat transfer coefficient at crank angle θ . The corresponding mean effective gas temperature is calculated as

$$\bar{T} = \frac{1}{360.\bar{h}}\int_0^{360} h\,(\theta\,)T(\theta\,)\,d\theta \tag{7}$$

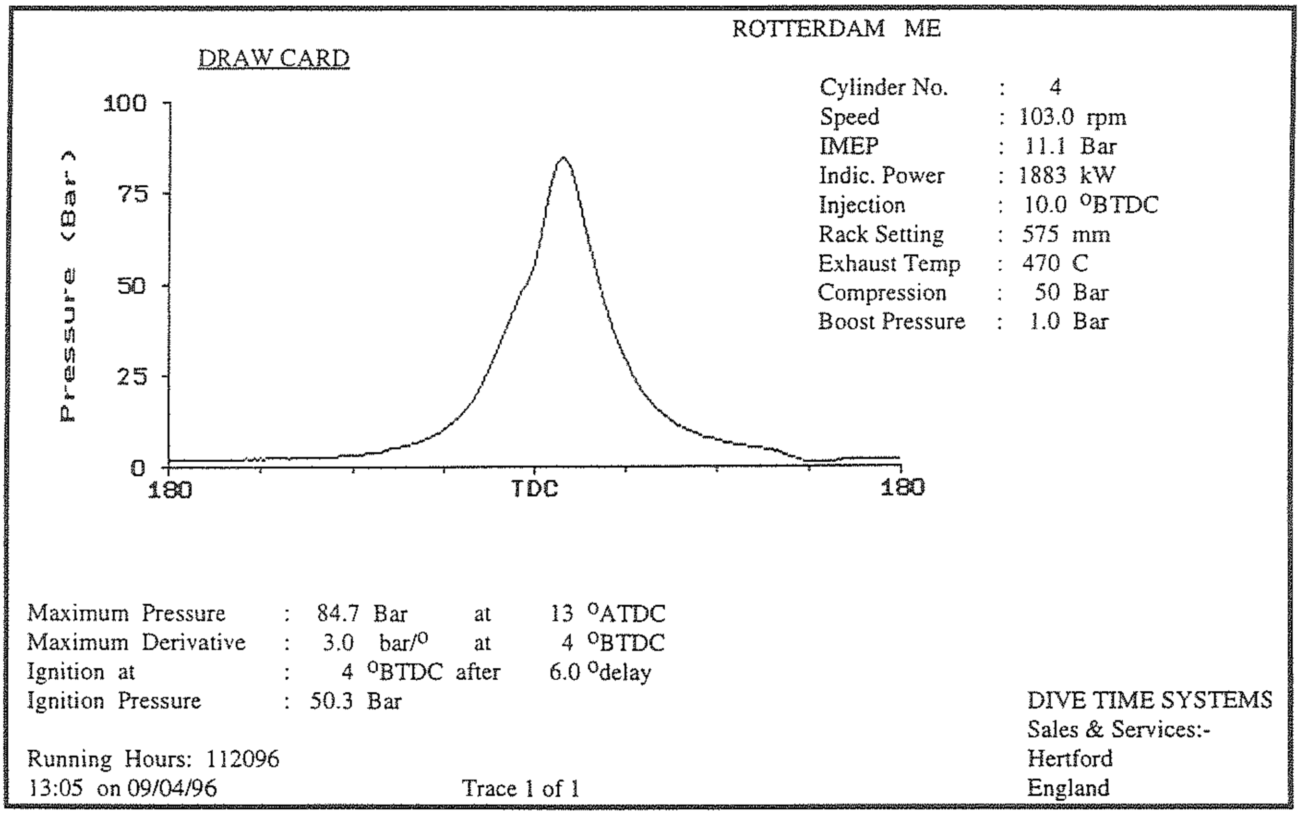
where T is the instantaneous gas temperature averaged over the gas volume at crank angle θ . For four stroke engines, the integral limits are over 720 degrees of crankangle.

3. EXPERIMENTAL VALIDATION

The applicability of DECSIM to medium and slow marine engines was experimentally investigated by Kortekaas (1996) on board two ships. The engines investigated are detailed in Table 1. A portable Malin 3000 diesel engine performance analyser was used to measure the pressures occurring in the engine cylinders during the combustion cycle. This equipment can process engine data directly to give information on fuel injection timing and the power output of each cylinder, or the data can be down-loaded to a PC. Complementary PC software provides the capability of monitoring engine performance and degradation over a period of time. Thus long term maintenance schedules can be devised based on actual working loads of individual engines. The software also displays graphs comparing individual cylinder power outputs as a visual aid to achieving a balance of power loads on the crankshaft. A full analysis of each cylinder requires the connection of both a pressure transducer to a standard cylinder indicator cock and attachment of an optical speed sensor. Slow speed two stroke diesel engines also require an angular velocity sensor (AVS) to measure variations in the rotational velocity of the crankshaft. This is due to the engine speed slowing down during the compression stroke of each cylinder and speeding up during the working stroke. The AVS measures and corrects for this variation. Data are sampled at every degree during the combustion cycle for engine speeds up to 1800 revs per minute and at two degree intervals above this speed. From the sampled data, the Malin 3000 system can produce graphs showing cylinder pressure and volume, cylinder pressure and crank angle or the rate of cylinder pressure change with crank angle. A typical display showing the variation of cylinder pressure with crank angle is shown in Figure 1 for a Sulzer 8RND90M engine.

Table 1 Engine Details

Engine	Description	Stroke (m)	Bore (m)
Sulzer 8RND90M	2 stroke, loop scavenging main propulsion engine	1.55	0.9
B&W 7L90Gb	2 stroke, uniflow scavenging main propulsion engine	2.18	0.9
Man/Sulzer 12AS25/30	4 stroke, generator prime mover	0.3	0.25
Pielstick 6PA5L255	4 stroke, generator prime mover	0.27	0.255



ROTTERDAM ME

DRAW CARD

Cylinder No. : 4
Speed : 103.0 rpm
IMEP : 11.1 Bar
Indic. Power : 1883 kW
Injection : 10.0 °BTDC
Rack Setting : 575 mm
Exhaust Temp : 470 C
Compression : 50 Bar
Boost Pressure : 1.0 Bar

Maximum Pressure : 84.7 Bar at 13 °ATDC
Maximum Derivative : 3.0 bar/° at 4 °BTDC
Ignition at : 4 °BTDC after 6.0 °delay
Ignition Pressure : 50.3 Bar

Running Hours: 112096
13:05 on 09/04/96

Trace 1 of 1

DIVE TIME SYSTEMS
Sales & Services:-
Hertford
England

Figure 1. Pressure Crank Angle Diagram for Sulzer 8RND90M Engine

The values of engine cylinder pressure variation with crankshaft angle, maximum cylinder pressure, indicated mean effective pressure, and fuel consumption, predicted by DECSIM, were compared with the experimental results obtained from each engine using a Malin 3000 Diesel Engine Performance Analyser. The results are summarised below in Table 2.

Table 2 Comparison of Results

Engine	Predicted	Measured	Deviation %
Sulzer 8RND90M IMEP (bar)	10.96	11.1	-1.3
Indicated Power (kW)	1855	1883	-1.5
Pmax (bar)	82.6	84.7	-2.5
B&W 7L90GB IMEP (bar)	12.5	12.9	-3.1
Indicated Power (kW)	2574	2657	-3.1
Pmax (bar)	100.5	108.5	-7.4
Man/Sulzer 12AS 25/30 IMEP (bar)	15.46	15.5	-0.3
Indicated Power (kW)	137.7	137	+0.51
Pmax (bar)	91.4	92.2	-0.9
Pielstick PA5 L255 IMEP (bar)	13.85	14.0	-1.1
Indicated Power (kW)	143.6	146	-1.6
Pmax (bar)	122.3	122.2	+0.1

4. APPLICATIONS OF DECSIM

4. 1 Fault Diagnosing

All three of the Pielstick PA5 L255 diesel engine electric generators on board the MV Raleigh Bay, had engines that were significantly down on their design output of 1100 kW for a considerable period of time. The ship had been docked in 1994 for survey as part of the extension of the conditions of class by the survey firm. Representatives from Pielstick checked the various pump timings, opened up one fuel pump unit and the turbo blower. Their recommendation was to renew all turbo blower housings, all fuel pump plungers and barrels and delivery valve assemblies. When one of the authors (HK) joined the ship, all renewals and overhauls had been done but the expected improvements had not been achieved. Due to high exhaust temperatures, the power of one engine was limited to 700 kW and the other two were limited to 500 kW. The ship owners, Nedlloyd, provided the author with a Malin 3000 diesel engine performance analyser. Using the Malin 3000 analyser, the author obtained experimental data and tried a number of ignition timings but to no avail. DECSIM was used to predict power output and the engine fuel timings were changed according to those used with DECSIM. The engine was run with the new settings but it still experienced high exhaust temperatures of 612°C before the turbo charger. The boost pressure obtained was about 0.2 bar less than the design value of 1.7 bar. The disparity between the predicted data of DECSIM and the experimental data from the Malin 3000 analyser led the author to conclude that the problem was not related to fuelling but to exhaust gas flow rates. It was with some reluctance however, that he decided to have the turbocharger opened up for inspection since it had already been the subject of a recent survey. When the turbocharger was opened up, it was found that the nozzle ring of the axial flow turbine was deformed and the surface of the shroud very rough as a consequence of the high exhaust temperatures. Once fixed, the predictions by DECSIM were very similar to the experimental values obtained with the Malin 3000 analyser. Experiments with the effect of fuel timing on power output using DECSIM showed a close correspondence with the measured values. The predicted ignition delay periods were also very close to the measured values. On another ship, MV Nedlloyd Colombo (14 years old) the Sulzer RLB type main engine had a low output. DECSIM was used to predict power according to present timing settings and then new values for fuel pump settings were used. The timings were adjusted in the main engine and the predicted increase in power was achieved.

4. 2 Insulating Combustion Chamber Components

The reduction of heat losses to the coolant system is of interest to engineers for a variety of reasons, including better thermal efficiency, lower thermal component stresses and a reduction in the size of cooling equipment required. In DECSIM, the heat flow paths through the piston, cylinder lined and piston are modelled as a thermal resistance network, which permits the calculation of individual bulk temperatures of these items during a simulation run. A study was made by Lawrence and Goodwin (1993), using DECSIM, into the effects on engine performance of using ceramic materials such as partially stabilised Zirconia (PSZ) for combustion chamber components. The engine simulated for this study was a 6V53T Detroit Diesel two stroke uniflow high speed diesel engine. The engine was chosen because of its strong family similarity with the very much larger Detroit 16V149TI, used in the RAN FFG7 frigates where the use of ceramics was being contemplated.

The engine was modelled in DECSIM initially without any ceramic insulation to provide a base line for comparison. Subsequent runs of the program were for PSZ layers of 1 mm, 2mm and 3 mm thickness. The thermal conductivity of PSZ was taken as 2.5 W/mK, that of cast iron as 53 W/mK and the fuel was assumed to be diesel fuel with a lower calorific value of 42 500 kJ/kg. Figure 2 shows the surface temperatures predicted using DECSIM. It can be seen that although the spatial mean temperatures are quite different for the three surfaces, the predicted temperature rise resulting from the maximum 3 mm layer of insulation is close to 300 K for each surface.

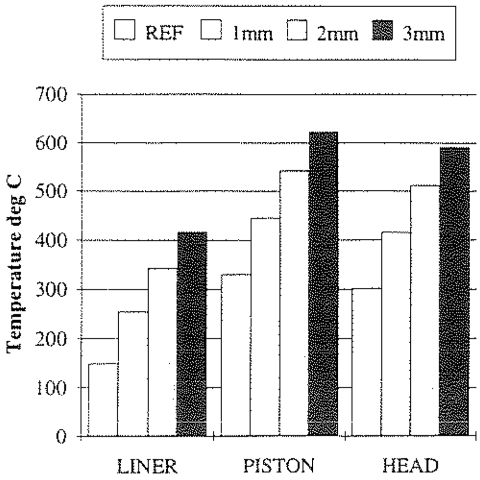


Figure 2. The effects of PSZ layer thickness on the average surface temperature. (Lawrence and Goodwin 1993)

4.3 Temperature Distribution in Engine components

Temperature distribution knowledge is an important pre-requisite for predicting thermal stress levels in combustion chamber components. Engine simulation models are useful for determining the bulk temperatures of combustion chamber components and showing general trends but they do not provide any detail of temperature distributions within the components. It is necessary to use finite element modelling in conjunction with an engine cycle simulation program such as DECSIM. The finite element method is a well established thermal analysis technique. The approach is illustrated here using a finite element model created of a Detroit Diesel 6V53T piston assembly shown in the Figure 3.

The piston type used in this engine is comprised of two separate parts, a crown with a gudgeon pin support boss and a full length skirt. When assembled, these parts form a well above the gudgeon pin which is fed with oil by one central hole through the gudgeon pin and drained by two side holes. The motion of the piston up and down the cylinder shakes the oil around the inside surfaces of the piston to enhance the cooling effect of the oil. This type of piston is often referred to as a cocktail shaker piston. Values for the cooling oil heat transfer coefficients on the underneath of the piston were calculated using the relationship suggested by Tyrrell (1987) for cocktail shaker pistons. The mean effective gas temperature in the cylinder and heat transfer coefficient predicted by DECSIM according to equations 6 and 7 are averaged both in time and spatially. Local heat transfer coefficients were assigned to the piston surfaces using the DECSIM values and empirically defined curves outlined by French (1969) for the spatial distribution of heat fluxes. The thermal analysis was performed using the Strand 6 finite element program on a PC computer.

Figure 4 shows a typical temperature distribution obtained using a standard piston for full load at 2800 rev/min.

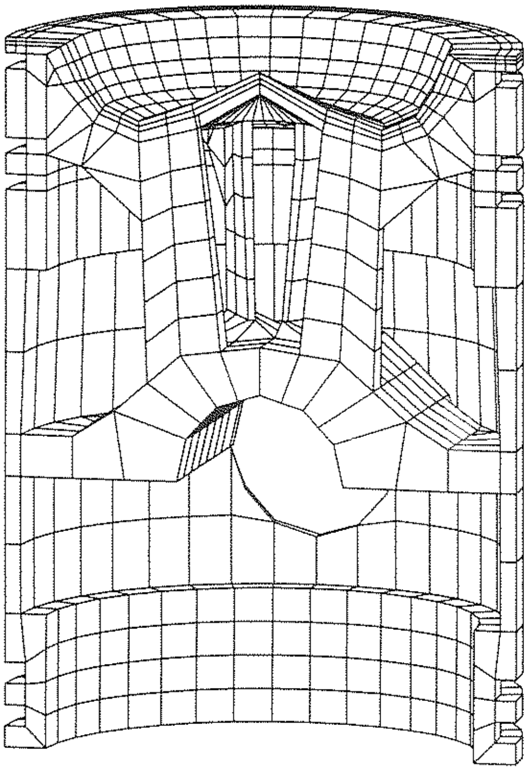


Figure 3 Finite Element Model of Detroit 6V53T Piston.

Values of the ten isotherms have been omitted for clarity. The maximum isotherm value in this case was 554 C, the minimum 116 C. This diagram graphically illustrates the intense temperature gradients in the piston crown.

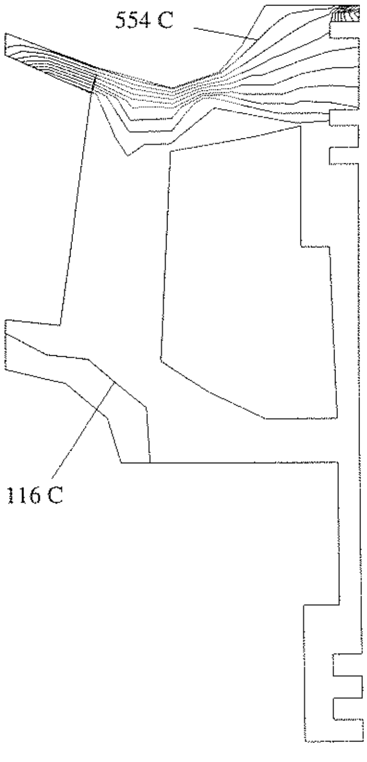


Figure 4. Predicted distribution of temperature isotherms in the standard uninsulated piston

4.4 Cooling System Operating Characteristics

An important part of the design loop in the design of marine engine cooling systems is to ensure that the system will operate at the desired cooling water flow rate. The pump, pipe, heat exchanger and engine system resistance curve as illustrated in Figure 5, depicts how the head required to overcome system friction increases with increasing flow. The intersection of the cooling water pump head-flow curve with the system resistance curve dictates the system operating point. Changes to the system resistance such as a different heat exchanger, changes to valve numbers or types or in the layout of pipework will result in a different operating point. A different pump will also result in a different system operating point. DECSIM incorporates a cooling system sub model which permits the effect on the system operating point due to changes in the system component resistances to be calculated. This is important when comparing the merits between compact, high pressure drop, heat exchangers with attendant high pump head duties and larger, low pressure drop heat exchangers with smaller pump head duties.

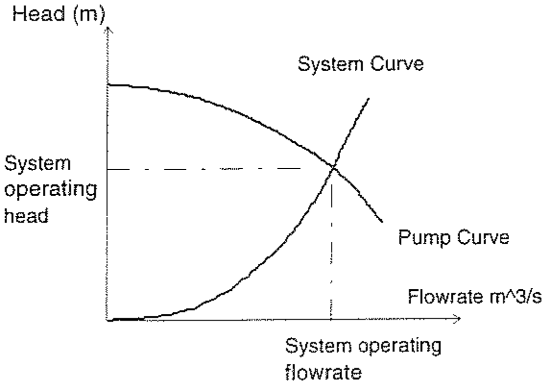


Figure 5 Cooling System Operating Point.

5. DISCUSSION AND CONCLUSIONS

In this paper DECSIM, a PC- based computer simulation package for diesel engine performance predictions has been described. The program has been designed using a modular concept and is thus easy to expand. The predictions of DECSIM has been compared with two medium speed four stroke and two slow speed two stroke marine diesel engines. The predicted performance of these engines under steady state operating conditions was in good agreement with the experimentally measured values. The greatest deviation was for the two stroke diesel engines. This may be due to the single zone scavenging model used in DECSIM for two stroke engines which tends to underestimate the charging efficiency (Sher 1991). A more comprehensive scavenging model for two stroke engines is being investigated as part of the ongoing development of DECSIM. However the results obtained confirm the use of DECSIM for trend analysis predictions.

It has been shown that DECSIM:

- can be used as a tool to assist marine engineers in fault diagnosing,
- can also be used for the prediction of average temperatures for combustion chamber components,
- can be used in conjunction with a finite element analysis study to predict temperature distribution within combustion chamber components,
- can be used to model cooling system behaviour and establish system operating characteristics.

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