1. INTRODUCTION

The ultimate goal of MET is to train cadet as a responsible and well-educated licensed seafarer who is certified to be compliant with the International Convention on Standards of Training, Certification and Watchkeeping for seafarers (STCW95) and the related International regulations. During the latest decades, experts, who are engaged in MET, are bending themselves to research and discuss how to improve the effect of MET with an effective and convenient method. Most of them tend to use marine simulator as an alternative.

In order to comply with the related International regulations and requirements, to gain higher safety in management and operation of propulsion system, and benefit for engineers and operators in acquiring skills embracing the correct employment of propulsion system, a real-time ship Propulsion System Simulator (PSS) has been developed as one of the most important sub-systems of full-mission ERS. This paper deals with the characters of propulsion plants, and establishes the real-time simulated mathematical models of propulsion plants based on the method of control volume. The main modeled elements consist of the main diesel engine, the fixed pitch propeller, the ship hull, the remote/local control levers, the dynamic and control systems which serve for main diesel engine, i.e. fuel oil system, lubricating oil system, starting and control air system, cooling water system, scavenge air system, exhaust gas system and manoeuvring system. Especially, the hull-engine-propeller matching model, the marine diesel engine model, the dynamic and control system models are introduced in detail. At the same time, a real-time simulation algorithm is described to meet the demands of rapid response, long running duration and little error accumulation of simulator.
2. PHYSICAL MODEL

The simulated physical model is able to represent the various elements of the propulsion system linked together in a way where the functional relationship between input and output variables are described in terms of functions and differential or algebraic equations[1]. The modeled ship propulsion system and overall functional scheme are shown in Fig.1.

![Fig.1 Modeled Propulsion System](image)

3. MATHEMATICAL MODELS

3.1 Hull-Engine-Propeller Matching Model

According to the actual data of ship trial (shown in table 1), the corrected propeller rotating torque $M_p$, propeller propulsive force $T_p$, ship resistance force $R$, propeller consumed power $P_p$ and the engine indicated power $P_i$ can be defined as [2]:

\[
M_p = 3294.0C_M n_p^2
\]
\[
T_p = 3059.4C_T n_p^2
\]
\[
R = 6.627C_R v_s^2
\]
\[
P_p = 20686.0C_M C_R n_p^3
\]
\[
P_i = 24393.6C_M C_R n_p^3
\]

Where, $C_R$ is a gain factor, which can express different navigation conditions and hull conditions of the modeled ship. It is described as:

\[
C_R = C_{R1} C_{R2} C_{R3} C_{R4} C_{R5} C_{R6} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdOTS
respectively.

### 3.2.1 Fuel Oil Injecting System
Fuel oil injecting system is to supply the high quality, controllable quantity fuel oil to the combustion chamber during the well-timed shaft angles. It includes the fuel injector pump, the high pressure pipes and the injectors [4] (shown in Fig.2).

![Fig.2 Fuel Oil Injecting System](image)

Fuel injector pump equations can be described as:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \rho u \cdot \frac{\partial A}{\partial x} = 0 \\
\frac{m_f}{\partial t} + \rho = F_{\phi} + \sum p_i A_i - C_x - C_f \frac{dh}{dt} \\
d \rho = -\beta \frac{dV}{V}
\end{align*}
\]

The fuel oil flow equations in high pressure pipes are described as:

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \rho u \cdot \frac{\partial \psi}{\partial x} + \frac{\partial \psi}{\partial x} + 2k\psi = 0 \\
\frac{\partial \psi}{\partial x} + \frac{1}{\alpha^2} \left[ \frac{\partial \rho}{\partial t} + \mu \frac{\partial \psi}{\partial x} \right] = 0 \\
\frac{\partial \psi}{\partial t} + \mu \frac{\partial \psi}{\partial t} - \frac{1}{\alpha^2} \left[ \frac{\partial \rho}{\partial t} + \mu \frac{\partial \psi}{\partial x} \right] = 0
\end{align*}
\]

Where, the equations (12) and (13) can be simplified as:

\[
\frac{\partial \psi}{\partial t} + \mu \frac{\partial \psi}{\partial t} = 0
\]

Fuel injector equations can be described as:

\[
\begin{align*}
\alpha \frac{dN_f}{dt} &= f_i \mu_i - \beta_f \frac{dz}{dt} - \xi \mu_i f_i \frac{2}{\rho} \left[ p_f - p_c \right] \\
\frac{m_f}{\partial t} &= f_i p_f - C_x (z + z_0)
\end{align*}
\]

Where,

\[
\beta = \begin{cases} 
0 & \text{When the needle is running.} \\
1 & \text{When the needle isn't running.}
\end{cases}
\]

\[
\xi = \begin{cases} 
0 & (p_f - p_c < 0) \\
1 & (p_f - p_c > 0)
\end{cases}
\]

The real fuel injection delay angle can be calculated from the initial fuel injection delay angle and the main engine speed, which is defined as:

\[
\Delta \phi_E = \Delta \phi_E / (n/n_0)
\]

#### 3.2.2 Combustion System
In this section, the triangular combustion model is applied (shown in Fig.3). At the same time, several modifications have been made to meet the demand for failure simulation in full running range described briefly below.

![Fig.3 Triangular Combustion Model](image)

Considering the influence of performance failures to combustion procedure, a term called combustion efficiency is introduced into the heat releasing process. The term is defined as the ratio of completely burned fuel to injected fuel, which is the function of excess air factor \( \alpha \) defined in the reference [5]:

\[
\eta_x = \begin{cases} 
3\alpha / 5 & (\alpha < 1.25) \\
(\alpha + 1)/3 & (1.25 \leq \alpha \leq 2) \\
1 & (\alpha > 2)
\end{cases}
\]

Then the rate of released heat can be defined as

\[
\frac{\delta q}{\delta \phi} = \begin{cases} 
\eta_x \cdot q_1 & \phi < 0.35 \Delta \phi \\
\eta_x \cdot q_2 & 0.35 \leq \phi \leq 0.65 \Delta \phi \\
\eta_x \cdot q_3 & \phi > 0.65 \Delta \phi
\end{cases}
\]

Where,

\[
q_1 = \frac{q_{\text{max}}}{0.35 \Delta \phi} (\phi - \phi_{FB})
\]

\[
q_2 = -\frac{0.85q_{\text{max}}}{0.35 \Delta \phi} (\phi - \phi_{FB} - 0.35 \Delta \phi) + q_{\text{max}}
\]

Journal of the JIME Vol.39, No.12
\[ q_3 = -\frac{0.155}{35 K_{\varphi}} (\varphi - \varphi_{\varphi}) \Delta \varphi \]..........(25)

Where, the maximum rate of released heat is:
\[ q_{\text{max}} = \frac{2}{0.7455 K_{\varphi}} \]..........(26)

The ignition angle is defined as:
\[ \varphi_{\eta} = \begin{cases} 
-2 & e < 0.66 \\
40(e + 0.66) - 2 & 0.66 \leq e \leq 0.91 \\
50(e - 0.91)/9 - 3 & e > 0.91 
\end{cases} \]..........(27)

The heat release duration angle is defined as:
\[ \Delta \varphi = \Delta \varphi_0 (\alpha_m/\alpha_m^0)^{0.6}(n/n_0)^{0.5} \]..........(28)

The combustion ratio of fuel oil is defined as:
\[ m = m_0 (\Delta \varphi_0/\Delta \varphi_0)^{0.5}(n_0/n)^0.8(p_a/p_{\text{ref}})(T_a/T_0) \]..........(29)

The mechanical efficiency is defined as:
\[ \eta_m = 0.4(n-60) - 0.01 + 0.82 \]..........(30)

3.2.3 Exhaust Turbocharger System The basic theory of mathematical model to exhaust turbocharger is still the conservation of energy and mass. The mass and energy accumulation in the control volume is considered by means of equations (31) and (32) respectively [1].

\[ \frac{d(p_v)}{dt} = M_t - M_0 \]..........(31)

\[ \frac{d(p_{sv})}{dt} = M_t h_t - M_0 h_0 + M_f h_f + \Theta - P \]..........(32)

The power of turbocharger compressor is defined as:
\[ P_t = \frac{m_r}{\eta_{\text{ref}}(h_f-h_t)} \]..........(33)

The variety ratio of mass flowrate of exhaust gas from turbocharger is defined as:
\[ \frac{dm}{dt} = C_f \sqrt{\frac{RT}{\varphi_0}} \frac{p_t^0}{p_0} \]..........(34)

The variety ratio of mass flowrate of air from air compressor is defined as:
\[ \frac{dm_a}{dt} = \frac{P_0}{h_t-h_0} \eta_{\text{ref}} \eta_{\text{ref}} \]..........(35)

The increased temperature of compressed air is defined as:
\[ T_t = T_t - T_0 \left[ \left( \frac{p_t^0}{p_0} \right)^{\frac{1}{\gamma}} - 1 \right] \frac{1}{T_t \eta_{\text{ref}}} \]..........(36)

\[ \eta_{\text{ref}} = n_c \frac{T_t}{288} \]..........(37)

3.3 Dynamic and Control Systems
3.3.1 Manoeuvring System The control of propulsion system is performed by the levers: the telegraphs and engine side manoeuvring buttons and handwheel. The lever on the “Engine side manoeuvring console” can be set to either Manual or Remote position. In the Manual position, the engine is controlled from the engine side manoeuvring console by the push buttons START, STOP, and AHEAD/ASTERN. The speed is set by the “Emergency speed setting” by the handwheel. In the Remote position, all signals to the engine are electronic, the START, STOP, AHEAD and ASTERN signals activate the solenoid valves, and the speed setting signal via the electronic governor and the actuator. The electrical signal comes from the remote control system, i.e. the Bridge Control (BC) console, or from the Engine Control Room (ECR), if any.

In order to realize the safe manoeuvring, the seafarers must learn about the requirements of engine manoeuvring. Therefore, the safe manoeuvring sequence of propulsion system with telegraph is emphasized here (shown in Fig.4). The employed manoeuvring sequence diagram [6], given by the engine manufacturer, shows the functions as well as the delays which must be considered in respect to starting Ahead and starting Astern, as well as for the activation of the slow down and shut down functions. On the right of the diagram, a situation is shown where the order Astern is over-ridden by an Ahead order.

3.3.2 Dynamic Systems The level equation of fuel oil tank is described as:
\[ L_t(t) = L_{t,0} - \int C_{\text{ref}} \frac{F_{m}(t)}{A_p} dt + \int C_{\text{ref}} \frac{F_{m}(t)}{A_p} dt \]..........(38)

Here, only the level of fuel oil tank is given as
an example. Other tank's equations are defined as 
the same method.

PID controller equation is described as [7]:
\[ y_1 = y_0 + \frac{K_c(x_2-x_1)+1/T_i(x_2+x_1)+T_d(x_2-x_1+x_0)}{dt} \] (39)

Heat exchanger equation is:
\[ t_e(t) = t_i(t) - \frac{1.16 g \cdot F_{\text{MW}} \cdot (t_{e1}-t_{e1})}{\omega \cdot A_v} \] (40)

Here only gives an example of static model of
steam condenser.
Pump equation is described as [7]:
\[ Q = F_M \cdot C_{pv} \] (41)

The difference of filter pressure between inlet and
outlet is described as:
\[ DP(t) = DP_0 + \int_0^t C \cdot F_M \cdot C_{pv} \cdot dt \] (42)

3.4 Equation Solution
The fourth-order Runge-Kutta method is applied in
the algorithm of differential equation. This method is
reasonably simple and robust and is known to be very
accurate and well-behaved for numerical solution of
differential equations. Suppose that \( x_n \) is the value of
the variable at time \( t_n \), the Runge-Kutta formula takes
\( x_n \) and \( t_n \) and calculates an approximation for \( x_{n+1} \) at a
brief time later, \( t_n+h \). It uses a weighted average of
approximated values of \( f(t,x) \) at several times within
the interval \( (t_n,t_n+h) \). The formula is given by [8]:
\[ x_{n+1} = x_n + \frac{h}{6} \left( k_1 + 2k_2 + 2k_3 + k_4 \right) \] (43)

Where,
\[ k_1 = f(t_n,x_n) \] (44)
\[ k_2 = f(t_n + \frac{h}{2}, x_n + \frac{k_1}{2}) \] (45)
\[ k_3 = f(t_n + \frac{h}{2}, x_n + \frac{k_2}{2}) \] (46)
\[ k_4 = f(t_n + h, x_n + k_3) \] (47)

4. REAL-TIME SIMULATION ALGORITHM
In order to meet the demand of rapid operational
response, long running duration and little error accumulation for PSS, a new algorithm was made based on the control volume model. Within the possible running range of propulsion plant, running speeds \( n_1, n_2, \ldots, n_{10} \) and fuel racks of engine \((s_1, s_2, \ldots, s_{10})\) were selected, and thermodynamic variables under each running speed \( n(i=1, 2, \ldots, 10) \) and each fuel rack \( s(i=1, 2, \ldots, 10) \) were calculated with the control volume method which formed a variable matrix \( A \) [2]:

\[
A = \begin{bmatrix}
a_{1,1} & a_{1,2} & \cdots & a_{1,n} \\
a_{2,1} & a_{2,2} & \cdots & a_{2,n} \\
\cdots & \cdots & \cdots & \cdots \\
a_{m,1} & a_{m,2} & \cdots & a_{m,n}
\end{bmatrix}
\]

Assume the present running speed is \( n \) and actual fuel rack is \( S \) during simulation, thermodynamic variables in vector \( B \) under running speed \( n \) and the fuel racks \( s(i=1, 2, \ldots, 10) \) are firstly gotten with the Newton interpolation method as:

\[
B = \begin{bmatrix}
b_1 \\
b_2 \\
\vdots \\
b_n
\end{bmatrix}
\]

Then the actual thermodynamic variable \( C \) can be gotten under actual running speed \( n \) and actual fuel rack \( S \) as

\[
C = \frac{(s_{i+1} - s_i) (s_{i+1} - s_{i-1})}{(s_{i+1} - s_{i+2}) (s_{i-1} - s_{i-2})} b_{i+1} + \frac{(s_{i+1} - s_i) (s_{i+1} - s_{i-1})}{(s_{i+1} - s_{i+2}) (s_{i-1} - s_{i-2})} b_{i+2}
\]

Where \( s_i < S < s_{i+1} \).

A new running speed of diesel engine \( n' \) and the ship speed \( v' \) can be calculated as:

\[
n' = n + (M_x \times \text{sgn}(D) - M_y \times \text{sgn}(n) - M_z \times \text{sgn}(n)) / 2 \pi / \omega \cdots (51)
\]

\[
v' = v_x + (T \times \text{sgn}(n) - R \times \text{sgn}(v_x)) / m_1 / (1 + 0.06) \cdots (52)
\]

By this algorithm, thermodynamic variables under any performance condition can be obtained with only eleven interpolating calculations and without plenty of iteration calculation of differential equation which meets the demand of real-time simulation. As every performance condition is computed from the variable matrix \( A \) and has nothing to do with the former running points, it can avoid error accumulation in computation and satisfies the requirement of long running duration of PSS.

The mathematical models of propulsion system discussed in this paper have been realized by suitable algorithm in microcomputer, which have been confirmed by experiment in applications of PSS, and have obtained satisfactory result. The calculated results are compared with the data of ship trial and shown in table 2 [9]. They can realize the requirement of rapid response, long running duration and little error accumulation. One of the Man-Machine Interfaces is shown in Fig.5 as an example.

### Table 2 Comparison between Experimental and Simulated results

<table>
<thead>
<tr>
<th>Physical parameter</th>
<th>Unit</th>
<th>Simulated value</th>
<th>Experimental value</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine rated speed</td>
<td>r/min</td>
<td>88</td>
<td>88</td>
<td>0</td>
</tr>
<tr>
<td>Cylinder indicated power</td>
<td>kW</td>
<td>2 776.8</td>
<td>2 778</td>
<td>-0.043</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>g/(kW.h)</td>
<td>162.56</td>
<td>165.87</td>
<td>-1.996</td>
</tr>
<tr>
<td>Average indicated pressure</td>
<td>MPa</td>
<td>1.56</td>
<td>1.58</td>
<td>-1.516</td>
</tr>
<tr>
<td>Compress endpoint pressure</td>
<td>MPa</td>
<td>12.03</td>
<td>12.05</td>
<td>-0.166</td>
</tr>
<tr>
<td>Max. combustion pressure</td>
<td>MPa</td>
<td>12.67</td>
<td>12.60</td>
<td>0.371</td>
</tr>
<tr>
<td>Maximum gas temp.</td>
<td>°C</td>
<td>1587.7</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Exhaust gas average temp.</td>
<td>°C</td>
<td>339.3</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Exhaust gas temp.</td>
<td>°C</td>
<td>307.5</td>
<td>310</td>
<td>-0.806</td>
</tr>
<tr>
<td>Exhaust gas flow</td>
<td>kg/s</td>
<td>6.0412</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Turbocharger rated speed</td>
<td>r/min</td>
<td>12 192</td>
<td>12 280</td>
<td>-0.717</td>
</tr>
<tr>
<td>Turbocharger inlet pressure</td>
<td>MPa</td>
<td>0.1962</td>
<td>0.2039</td>
<td>-3.776</td>
</tr>
<tr>
<td>Turbocharger outlet pressure</td>
<td>MPa</td>
<td>0.1015</td>
<td>0.1020</td>
<td>-0.409</td>
</tr>
<tr>
<td>Turbocharger inlet temp.</td>
<td>°C</td>
<td>390.2</td>
<td>385</td>
<td>1.356</td>
</tr>
<tr>
<td>Turbocharger outlet temp.</td>
<td>°C</td>
<td>265.4</td>
<td>255</td>
<td>4.082</td>
</tr>
<tr>
<td>Intercooler inlet temp.</td>
<td>°C</td>
<td>160.5</td>
<td>156</td>
<td>2.897</td>
</tr>
<tr>
<td>Intercooler outlet temp.</td>
<td>°C</td>
<td>42.1</td>
<td>38</td>
<td>10.868</td>
</tr>
</tbody>
</table>

Fig.5 Main Interface
5. FAILURE SIMULATION

It is well known that one of the major factors of accident prevention on board is the perfect theoretical and practical knowledge possessed by marine engineering officers and operators. However, mere theoretical understanding of propulsion system is not enough. Marine engineers must acquire a feel of physical sense in the operating condition. If the propulsion system is broken, the ship turns into nothing more than a drifting object, which is an extremely dangerous situation [10]. Therefore, PSS should also execute under emergency situation besides routine operation. This kind of training is very difficult to carry out on board ship and is therefore very economical in simulator training which can be of great benefit to seafarers' calm emotion and strong ability dealing with the urgent situations.

Those who have experience in simulator training recognize that it is an economical and safe way to gain years of sea skills in several weeks of intensive simulator training. It is widely known that it can reduce human errors and prevent catastrophic accidents or loss of life and property through the use of simulator-based training. The simulation system can simulate most of failures or accidents of propulsion system which happen scarcely on board ship and reinforce seafarers' ability to treat with emergency situations and casualties which can be of great significant to safe navigation at sea. The training of real-time simulation of ship propulsion system can help prevent equipment damage, reduce vessel downtime and increase operational reliability.

6. FUNCTIONS

Based on the analysis of physical and mathematical models, the software of real-time propulsion system simulator is developed. Its main missions are to realize Man-Machine Interfaces, mathematical models and data transfer among hardware, software and other ERS workstations.

PSS system can provide a cost-efficient shore-based training and evaluation platform for the training and evaluation of ship propulsion system rather than on ships in service.

Combining with automatic control characteristics and operation requirement of propulsion system on ships in service, PSS system can execute the functions of propulsion plant's starting, stopping, remote control, manual control and emergency control, safety protection, fault simulation, ACK(acknowledgement), operation recording, operation evaluation and fault alarming, etc [11].

The functions of PSS are based on two objectives: training function and evaluation function.

Training function especially stresses controllable operation environment and reality. It can provide a training platform for the trainees to improve operation skills, master operation methods and processes at some normal and abnormal conditions, and especially be proficient in emergency procedure and safety management.

Evaluation function particularly emphasizes on test and evaluation of trainee abilities about operation, management and problems solutions. PSS system can set some special operation condition, i.e. normal, abnormal and emergency work condition, to evaluate trainee's general ability (refer to Fig.6).

7. CONCLUSIONS

Different from other scientific educations, MET puts more emphases on the training for practical skills to cultivate responsible and well-educated licensed
seafarers who are certified to be compliant with requirements of the STCW95 Convention and the related Codes. It is now becoming common sense in maritime societies to use the simulators as testing tools in granting certificates.

Based on the mathematical model of propulsion system and the real-time simulation algorithm, a new real-time propulsion system simulator is developed. This simulator can provide a cost-effective shore-based training and evaluation platform for testing, evaluating and debugging for propulsion system rather than on ships in service. It can simulate most of failures or accidents of ship propulsion system and reinforce seafarers’ ability to treat with emergency situations and reduce accidents due to human factors, which may have significant impact on the safety and efficiency of navigation at sea. The trainees can not only acquire the knowledge regarding the operation of propulsion system in normal conditions, but also familiarize with emergency situations. In consequence, the trainee can be better prepared to deal with emergencies during operations on board ship. Especially, the emergency situations may be simulated and repeated as many times as it is necessary for the trainees to achieve proper training goals.

PSS system has been used successfully as one of MET tools not only in training marine engineering students, but also in training engineers since 2000, with which trainees have possibilities to develop operation skills, and be proficient in emergency procedures and safety management. It is benefited in preventing ship damage and catastrophic accidents, reducing human errors in operation and maintenance of ship propulsion system, and making ships safer.

NOTATIONS

\[ A \quad \text{area} \quad m^2 \]
\[ b \quad \text{channel width} \quad m \]
\[ B \quad \text{ship width} \quad m \]
\[ C \quad \text{coefficient} \quad --- \]
\[ D \quad \text{main engine running direction} \quad --- \]
\[ e \quad \text{cyclical fuel charge ratio of calculated condition to rated condition} \quad --- \]
\[ f \quad \text{sectional area} \quad m^2 \]
\[ F \quad \text{flowrate} \quad m^3/h \]
\[ g \quad \text{indicated value in Eq.41-42} \quad kg/h \]
\[ h \quad \text{the acceleration of gravity} \quad m/s^2 \]
\[ k \quad \text{channel depth in Eq.7-9} \quad m \]
\[ m \quad \text{stroke of injector pump in Eq.11} \quad m \]
\[ n \quad \text{specific enthalpy in Eq.32-33} \quad kJ/kg \]
\[ P \quad \text{the step size of calculation in Eq.43-47} \quad m \]
\[ q \quad \text{resistance coefficient of flow} \quad --- \]
\[ R \quad \text{proportional gain} \quad --- \]
\[ L \quad \text{depth} \quad m \]
\[ M \quad \text{mass} \quad kg \]
\[ N_m \quad \text{torque in Eq.1} \quad Nm \]
\[ n \quad \text{mass flowrate in Eq.31-32} \quad kg/s \]
\[ n \quad \text{rotation speed} \quad r/min \]
\[ p \quad \text{pressure} \quad Pa \]
\[ P \quad \text{power} \quad kW \]
\[ Q \quad \text{released heat in Eq.22} \quad kJ \]
\[ Q \quad \text{pump displacement in Eq.41} \quad m^3 \]
\[ R \quad \text{resistance} \quad kN \]
\[ s \quad \text{actual fuel rack} \quad --- \]
\[ S \quad \text{sailing distance} \quad m \]
\[ T \quad \text{temperature in Eq.40} \quad K \]
\[ T \quad \text{thrust in Eq.1} \quad kN \]
\[ t \quad \text{time} \quad s \]
\[ T \quad \text{draft in Eq.6-7} \quad m \]
\[ U \quad \text{temperature in Eq.37} \quad K \]
\[ T \quad \text{derivative gain} \quad s \]
\[ T \quad \text{integral gain} \quad s \]
\[ u \quad \text{flow velocity} \quad m/s \]
\[ v \quad \text{specific internal energy in Eq.32} \quad kJ/kg \]
\[ v \quad \text{speed in Eq.1,9} \quad m/s \]
\[ V \quad \text{specific volume in Eq.31} \quad m^3/kg \]
\[ v \quad \text{volume} \quad m^3 \]
\[ a \quad \text{velocity of sound in Eq.13-16} \quad m/s \]
\[ a \quad \text{excess air factor in Eq.21} \quad m/s \]
\[ x \quad \text{instant excess air factor} \quad --- \]
\[ \beta \quad =0, \text{when the needle valve closed} \quad --- \]
\[ \beta \quad =1, \text{when the needle valve opened} \quad --- \]
\[ \Delta \quad \text{difference} \quad o \]
\[ \phi \quad \text{rudder angle in Eq.5} \quad o \]
\[ \phi \quad \text{angle in Eq.22-28} \quad o \]
\[ \eta \quad \text{ignition angle} \quad o \]
\[ \eta \quad \text{efficiency} \quad % \]
\[ \eta \quad \text{combustion efficiency} \quad % \]
\[ \pi_r \quad \text{expanding ratio in turbocharger} \quad --- \]
\[ \theta \quad \text{angle from wind direction to ship sailing direction} \quad o \]
\[ \rho \quad \text{density} \quad kg/m^3 \]
\[ \tau \quad \text{duration since the latest hull} \quad \text{year} \]
cleaning in terms of year

$$\tau_i = 1.04 - 1.10$$

$$\omega$$ mean coefficient for heat exchange \( W/(m^2 \cdot K) \) of liquid film on pipe’s surface

$$\xi = 0, \text{ when } P_f - P_z \leq 0$$

$$\xi = 1, \text{ when } P_f - P_z > 0$$

$$\psi$$ function affected by air flow

$$\Theta$$ heat flow \( kJ/s \)

$$\Delta \phi$$ duration angle

**SUBSCRIPTS**

0 initialization value

1, 2, ..., n sequence

a air

B ballast

c coefficient

e engine

EV fuel injection delay angle

f, F fuel oil

FVI inlet valve of fuel oil tank

FVO outlet valve of fuel oil tank

FW fresh water

i indication

K turbo compressor

l level

m mass

machinery efficiency in Eq.30,33

M torque in Eq.1

meter in Eq.38,41,42

P propeller in Eq.1

pump in Eq.38,41

PV flow coefficient

R resistance

s ship

S saturation steam

mean entropy in Eq.33-36

t time

T thrust in Eq.1

temperature

gas turbine in Eq.33-34,37

V valve

W water

ZV fuel combustion delay angle

**REFERENCES**


