Thermal Management System Analysis of Marine Diesel Engine

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***Abstract*—A lumped parameter model is developed to study performance of marine diesel engine thermal management system. One dimensional flow equations combined with classical Webie combustion model and Woschni heat transfer model are employed to describe diesel's flow characteristic. Modeling results of heat release from diesel engine is validated against experimental data. Cooperated with experimental data based models of water pump and heat exchangers, thermal management system performance is analyzed while engine fresh cooling water outlet temperature is controlled to achieve a certain value by a PID temperature regulating valve. The results shown that inlet seawater temperature variation has relatively little effect on opening of regulating valve, but engine power output variation results in notably regulating valve opening fluctuation. Modeling results would be employed in an advanced submarine diesel engine system design.**

***Index Terms*—lumped parameter model, thermal management system, marine diesel engine**

I. Introduction

As a traditional high power density engine, diesel is widely used in ship propulsion system. Cooling performance degrades worse when fresh cooling water flowing through cylinder jacket achieves a higher temperature than normal point, which is usually controlled to be lower than 80℃. In shipboard centralized cooling system, thermal performance of each subsystem affects performance of other subsystems and consequently affects performance of the whole propulsion system. A self regulating temperature PID controlling valve is applied in engine fresh cooling water circuit to keep a relatively stable inlet water temperature. In traditional system, wax cylinder is used to create a bypass flow threshold. As an updated substitution of wax cylinder, a much more accurate regulating valve with a PID controller integrated is now usually applied in advanced engine thermal management system.

Many studies are conducted on cylinder cooling management, and definite conclusion is made as water temperature control is very important for diesel [1], these studies are usually conducted aiming for engine performance improvement [2]-[4]. But few studies are conducted on the integrated system aiming for a ship board centralized cooling system where diesel engine thermal management affects and is affected by other subsystem.

A lumped model for a 1000kW marine diesel engine thermal management system is presented in this study. Power output and heat release of diesel is calculated by widely accepted Wiebie combustion model and Woschni heat transfer model separately. Heat release rate of heat source in engine system is modeled by fitting curves based on experimental data. Heat transfer in seawater heat exchanger is modeled by empirical lumped parameter model. As air inlet temperature is an important parameter which affects engine performance. Flow in system is simulated by one dimensional mass conversation equations.

Performance of the ship diesel engine thermal management system is simulated at different power output and seawater inlet temperature.

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II. System Model

A. System Description

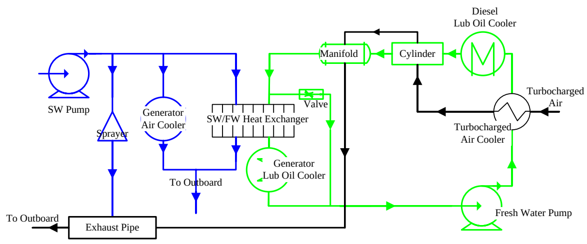

Figure 1. Advanced submarine diesel thermal management

Thermal management system of Virginia Submarine diesel generator is as shown in Fig. 1. In this system, air route, freshwater route and seawater route are stated in different lines. Freshwater/seawater heat exchanger is a high efficient plate model. Larger power output of diesel engine results in higher freshwater temperature flowing into thermostat and heat exchanger, therefore, more hot water is sent to heat exchanger for cooling and then joins together with the uncooled water.

A simple system sketch is shown as Fig. 2. Water from pump flows through diesel engine cylinder and splits to two pass, one bypass leads through air intercooler and then join the main pass leads from freshwater seawater heat exchanger. Heat transfer in air intercooler is important in the presenting model. A PID water temperature controlling valve is set at entrance of engine

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cooling water pipe to change fresh water flow rate into heat exchanger for cooling. If engine cooling water outlet temperature is greater than preset 80℃, then opening degree of the valve rises up, and if it is under 80℃, then valve opening declines down.

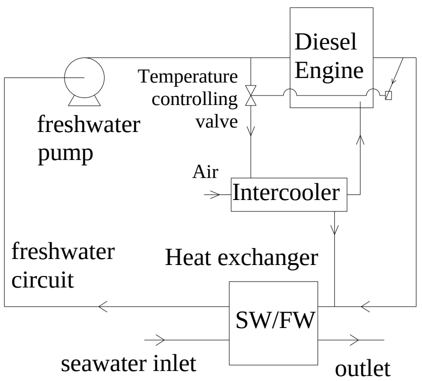

Figure 2. system sketch

Basic model parameters are as shown in Table I.

TABLE I. BASIC MODEL PARAMETERS

parameter	value
Engine model	Caterpillar 3512B/1000kW
Freshwater pump	$20m^3/h$
Air inlet temperature	~60℃
Sea water/fresh water heat exchanger model type	Plate heat exchanger
Feedback controlling strategy of temperature regulating valve	PID

B. Engine Performance Model

Performance of diesel is modeled by Wiebie combustion equations and Woshni heat transfer equations combining with experimental data based heat release model used to describe air intercooler. Other heat sources in system like fuel cooler and oil cooler are cooperated as part of diesel engine. Nomenclatures in following equations are the same as those stated in [5].

Mass conversation equation,

$$\frac{dm}{dt} = \sum mflx \tag{1}$$

Energy conversation equation,

$$\frac{d(me)}{dt} = \sum (mflx \cdot H) + \rho \frac{dV}{dt} - hA\left(T_{gas} - T_{wall}\right) \tag{2}$$

Enthalpy conversation equation,

$$\frac{d(\rho HV)}{dt} = \sum (\rho u A_{eff} H) + V\frac{d\rho}{dt} - h_g A\left(T_{gas} - T_{wall}\right) \tag{3}$$

Momentum conversation equation,

$$\frac{d(mlfx)}{dt} = \frac{d\rho A + \sum (mflx \cdot u) + 4C_f \frac{\rho u^2}{2}\frac{dxA}{D} - C_p A \frac{\rho u^2}{2}}{dx} \tag{4}$$

Heat release rate of combustion,

$$\frac{dQ_B}{d\varphi} = gfH_u \eta_u \frac{dX}{d\varphi} \tag{5}$$

Wiebie semi-empirical equation,

$$X = 1 - e^{-6.908\left(\frac{\varphi - \varphi_B}{\varphi_B - \varphi_C}\right)^{(m+1)}} \tag{6}$$

Heat transfer to cooling water,

$$\frac{dQ_w}{d\varphi} = \frac{1}{w} hA_s \left(T_{wall} - T_{gas}\right) \tag{7}$$

According to Waschni,

$$h = 129.8B^{-0.2}P^{0.8}T^{-0.55}v^{0.8} \tag{8}$$

Heat release rate from cylinder to cooling water is as shown in figure 2[6].A fitting relationship expression of proportion of heat release rate to fuel cell power output is educed here based on the experimental data. Percent of heat release from engine cooling water and engine power to overall heat production from fuel combustion declines as torque increases.

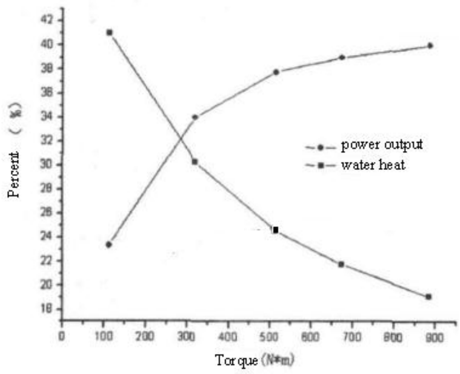

Figure 3. Heat release and power output

Heat exchange between turbocharged air and water, freshwater and seawater is described by traditional heat transfer equations employed for heat exchanger performance computation.

$$Q = KA\Delta T \tag{9}$$

where K is a coefficient educed by experimental data for a certain heat exchanger.

III. RESULTS AND DISCUSSION

Based on parameters from engine system in Virginia submarine, simulating results and experimental results are as shown in Table II.

TABLE II. MODELING RESULTS AGAINST EXPERIMENTAL DATA

Temperature value	Experimental result/℃	Simulating result/℃
Freshwater after FW/SW exchanger	33.9	28
Cylinder water inlet	82.8	
Freshwater outlet	86.1	80
Seawater inlet	26.7	22
Seawater outlet	34.5	31

Performance of thermal management is studied here at different environmental seawater temperature and different engine power output.

Inlet seawater temperature varies at different sea area, the difference can achieve as great as 20K. Affect of this kind of variation on opening of temperature controlling valve is as shown in Fig. 3. Engine power output is set at 90% rating power 900kW and inlet seawater temperature is set to be increasing linearly. And the evolution of engine cooling water outlet temperature and SW/FW heat exchanger seawater outlet temperature are as shown in Fig. 4.

At 90% rating engine power output, increasing of inlet seawater temperature results in a indistinct declining valve opening.

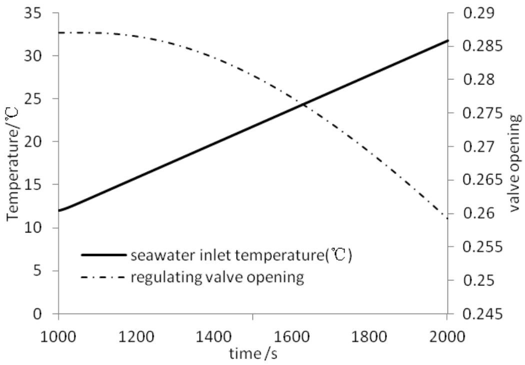

Figure 4. Effect of seawater inlet temperature on valve opening

As regulating valve opening changes little, engine cooling water outlet temperature fluctuates little. Increment of seawater temperature keeps about the same as seawater inlet temperature increases.

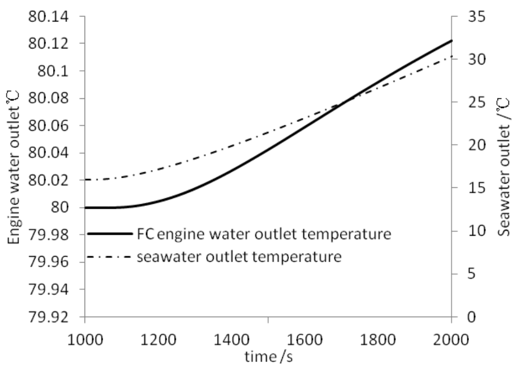

Figure 5. Effect of seawater inlet temperature on outlet water temperature

At different engine power output, heat release to cooling freshwater varies and affect of this kind of variation on opening of temperature controlling valve is as shown in Fig. 5. The evolution of engine cooling water outlet temperature and heat exchanger seawater outlet temperature are as shown in Fig. 5.

According to experimental data, diesel engine heat release rate acts following a cubic relationship against engine power output. As engine power increases linearly, opening of regulating valve decreases relatively rapidly at low power output less than 250kW, but after a fluctuating regulation, it shows a slowly declining line. Though diesel engine cooling water outlet temperature fluctuates like valve opening evolution line, seawater outlet temperature increases stably as engine power increases.

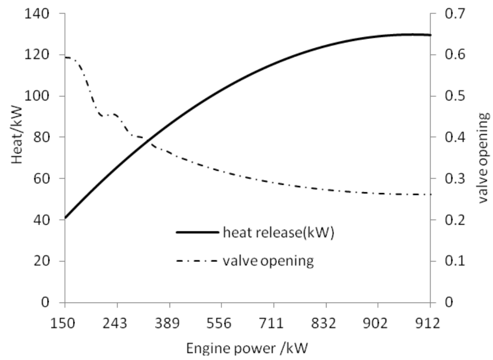

Figure 6. Effect of engine power output on valve opening

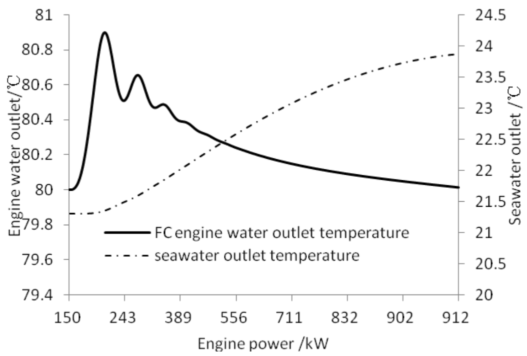

Figure 7. Effect of engine power output on outlet water temperature

SUMMARY

A lumped parametric system model is developed to study thermal management system performance of shipboard 1000kW diesel engine. Power output of engine is calculated by combining widely accepted combustion and heat transfer model. Heat release rate of engine to fresh cooling water is modeled by a fitting curve based on experimental data. Heat transfer in heat exchanger is modeled by empirical lumped parametric model.

Performance of a ship diesel engine thermal management system is simulated at different power output and seawater inlet temperature. The results shown that inlet seawater temperature variation has relatively little effect on opening of regulating valve, but engine power output variation results in notably regulating valve opening fluctuation.

REFERENCES

[1] D. M. Jiang, *et al.*, "Principle of internal combustion engine," 2000.

[2] C. Lehner, *et al.*, "Design and development of a model based feedback controlled cooling system for heavy duty diesel truck applications using a vehicle engine cooling system simulation," SAE Paper, 2001-01-0336, 2006.

[3] W. NessimA, *et al.*, "Simulation study of an advanced thermal management system for heavy duty diesel engines," in

Proceedings International Conference on Mechanical Engineering and Material Science, Shanghai, China, 2012
[4] F. Kitanoski, *et al.*, “An engine heat transfer model for comprehensive thermal simulations,” SAE Paper, 2006-01-0882, 2006.
[5] GT-Power User Manual, Version 6.2, Gamma Technology, Inc, September, 2006
[6] Q. W. Jiao, *et al.*, “The heat analysis of cooling water for diesel engine,” dissertation, Jinan: Shandong University, China, 2008.

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