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Modeling with Fault Integration of the Cooling and the Lubricating Systems in Marine Diesel Engine: Experimental validation

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Abstract: In this paper, physical models for the cooling and the lubricating systems for marine diesel engine have been developed. The main purpose of this modeling is to integrate some possible faults that may be produced, and then to analyze their effects on the overall marine diesel engine during operation. Faults may appear in the model as the variation of some parameters. The importance of this study is to prepare an important data base for the fault diagnosis and prognosis strategies that may be applied on Diesel engines. Experimentations on Marine Diesel engine test bench have been used for the validation of the proposed model.

Keywords: Engine Modeling, Cooling system, Lubrication system, Faulty mode operations.

1. INTRODUCTION

Requirements on diesel engines in terms of efficiency, fuel consumption, faulty mode operations, and environment have been increased during last decades. And due to the fact that the occurrence of any fault in the engine may decrease efficiency, increase fuel consumption, and increase toxic emissions, several works in fault diagnosis, prognosis and fault tolerant control have been published. The complexity of these studies resides in the fact that actual data about the engine in a faulty mode operation is difficult to be collected, because an important number of the faults that may be produced in the engine can't be injected during operation of the test bench. This makes the idea of developing accurate physical models, containing some of the physical parameters which may vary and generate faults is of high importance.

In this paper, we present models of two main components of the engine, which are the cooling system and the lubricating system. The main function of the cooling system is to maintain the engine at an optimum operating temperature. Several models have been developed for this system. In (Corbel, 1987) (Chang et al., 1991), (Nahim et al., 2015a) authors have developed cooling system models to be used in normal operations and to meet some design and sizing requirements. In (Salah et al., 2010), a dynamic model based on the thermal modeling has been developed for control purposes. (Yoo et al., 2000) and (Feenstra et al., 2000) have developed models for diagnosis purposes. In (De Persis and Kallesøe, 2009) and (De Persis and Kallesøe, 2008), authors have modeled the hydraulic network, the method is based on the network theory and the well-known analogy between electrical and hydraulic circuits. The second component that we present in this paper is the lubricating system. The main function of the lubricating system or lubricating circuits is to provide a protective layer, and to prevent metal to metal contact, which reduces friction and to absorb heat from the engine. Several studies have been developed in the literature for the modeling of the lubricating system. (Neu et al., 1977) has presented the lubricating system with parallel flow pipe networks. In (Haas et al., 1991), authors have studied the influence of oil on the engine operating pumps, (Chun, 2003) has presented a model summary of the lubrication system by treating the hydraulic system focusing on the oil flow in the different components.

The main contribution of this paper can be resumed by the development of a dynamic model for the cooling and lubricating systems taking in consideration hydraulic and thermal effects, and the interaction with other engine's subsystems, and also degradation processes (Nahim et al., 2015b). The developed model can be used to simulate the effect of fault occurrence on the system. It is validated by experimental results. It can then be used to validate the diagnosis, prognosis, predictive maintenance and fault tolerant control algorithms.

2. TEST BENCH

The test bench used in this work is a marine diesel engine manufactured by the company SIMB under the reference 6M26SRP1 (Fig. 1).

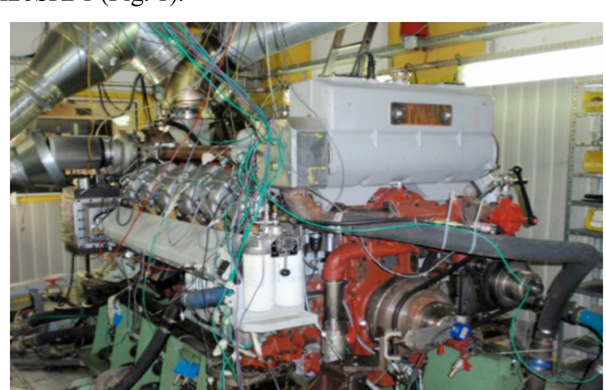

Figure 1: Test bench Baudouin 6M26SRP1

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The engine has six-cylinders with direct injection, a power ranging up to 331 kW, a maximum speed of 1800 rpm. The main characteristics of the engine are summarized in Table 1.

Table 1 Characteristic of the test bench

Characteristics	Value
Bore and stroke	150×150
Number of cylinders	6
Compression ratio	15.9
Number of valve per cylinder	14/1
Rotation according norm ISO 1204	SIH
Idling/(min^{-1})	650
Mass without water or oil/kg	1 870

3. COOLING SYSTEM

3.1 Description of cooling system

The cooling system is responsible of maintaining the temperature of the engine at an optimum operating temperature. It consists of several components as show in Fig. 2. The pump driven by the crankshaft, ensuring the flow of fresh water in the system, the water passes through the engine block to cool it. At the outlet of the engine block, the water thermostat that takes the flow rate of the coolant temperature (freshwater) to the pump (if cold) or to the water heat exchanger (if hot). This Operation helps to regulate the temperature of the system. Some of possible faults that may be produced in the cooling system and presented in this paper are:

- Faults in the pump: wear, water leaking.
- Faults in the thermostat: locked.
- Fault in the heat exchanger: leaking, fouling.

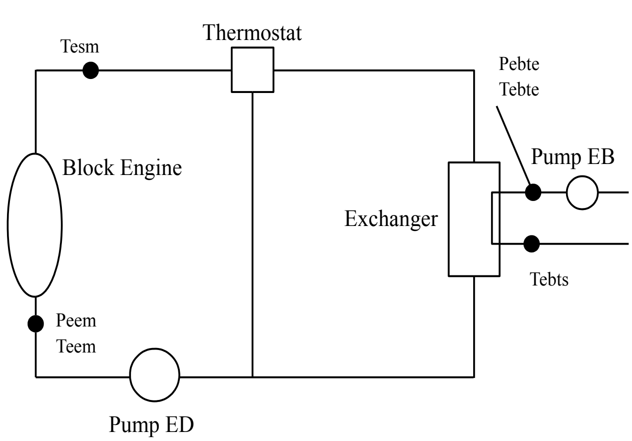

Figure 2: Components of the Cooling system.

3.2 Modeling of system

The water passes through the engine block for cooling, the heat flow exchanged depends on the flow rate of fuel injected into the cylinders ($\dot{m}_f$). Is given by the following equation (Heywood, 1988):

$$\varphi_{Moteur} = b_1 \left[\dot{m}_f / A_p \right]^{b2} \quad (1)$$

Where b_1 and b_2 are constants, A_p is the internal area of cylinder (m^2), $\dot{m}_f$ is the flow of fuel (l/h) entering the cylinder.

Similarly, the fresh water exchange heat with the sea water, the heat flow is described by the following equation (Salah, 2006):

$$\varphi_{Ech} = \varepsilon_{eche}.c_{ped}.K_{th}.Q_{ed}.(T_{ebte} - T_{esm}) \quad (2)$$

Where ε_{eche} is the efficiency (%) of the heat exchanger (fresh water-sea water), c_{ped} is the specific heat of water (kj/kg. C°), k_{th} is the opening of thermostat (%). Q_{ed} is the flow of water (l/sec), T_{ebte}, T_{esm} are respectively the temperature of entrance of sea water in the heat exchanger, and the temperature of the fresh water at the outlet of the block engine(C°).

The thermostat is the device that controls the flow of fresh water according to the engine temperature. Fresh water is taken to the engine if the temperature is low and to the heat exchanger if the temperature is high. The opening command thermostat to the heat exchanger (K_{th}) is given by the following equations:

$$\begin{cases} \bullet\ K_{th} = 0 (Tesm < 77) \\ \bullet\ K_{th} = \dfrac{Tesm - 77}{87 - 77} (77 < Tesm < 87) \\ \bullet\ K_{th} = 1 (Tesm > 87) \end{cases} \quad (3)$$

The pump in the circuit creates a pressure difference which depends on the angular velocity of crankshaft W. The flow of the pump depends on the hydraulic resistance circuit components. Assuming that all system components assimilated (against their flow resistances) at lengths of pipes L_i and diameters d_i (i refers to the i component, engine block heat exchanger, pump ...), the resistances of the lines are expressed by the following equations (White, 1994):

$$R_i = 128.\mu.L_i/(\pi.D_i^4) \quad \text{(Laminair)} \quad (4)$$

$$R_i = 0,241.L_i.\rho^{0.75}.\mu^{0.25}.D_i^{-4.75} \quad \text{(Turbulent)} \quad (5)$$

Where R_i is the hydraulic resistance for a component, L_i and D_i are respectively the equivalent length and diameter for this element (m). μ is the dynamic viscosity and ρ is the density (kg/m^3).

The model below represents the modeling of cooling circuit (Paradis et al., 2002) (Heywood, 1988). Giving the temperature at the outlet of the block engine, the heat exchangers, and the pressure at the outlet of two pumps.

Temperature water at the engine outlet:

$$C_B.\dot{T}_{esm} = b_1 \left[\dot{m}_f / A_p \right]^{b_2} - Q_{ed}.c_{ped}.(T_{esm} - T_{eem}) \quad (6)$$

Where C_B is the engine block capacity (kj/ C°). T_{eem} is the temperature of fresh water at the inlet of the engine block engine (C°).