

Development of a 1D Simulation Model for BEV Thermal Management Systems

-(Part 2) Modeling of Oil Behavior in the Refrigeration Cycle-

Yu Yamashita¹⁾ Yousuke Yasuda¹⁾ Yusuke Sato¹⁾ Tomohiro Sudo¹⁾

1) DENSO Corporation, 1-1 Showa-cho, Kariya, Aichi, 448-8661, Japan (E-mail: yu.yamashita.j6z@jp.denso.com)

KEY WORDS: air conditioner, refrigerant, algorithm/modeling, oil circulation ratio, oil retention (D1)

In battery electric vehicles (BEVs), engine waste heat is not available, so the thermal management system for the cabin and the devices governs the driving range, and its operating modes have diversified. In the first report of this series, a 1D model including the heat pump was developed with both computational speed and accuracy, but it covers only the thermo-fluid behavior of the refrigerant. Since the compressor is lubricated by oil dissolved in the refrigerant, the oil circulation ratio (OCR) governs the balance between lubrication and efficiency: oil retained in each component lowers the OCR. This report presents a method that predicts the oil amount in each component from the underlying physics and integrates it over the cycle to predict the OCR.

Components such as heat exchangers have complicated internal flow paths, so the oil behavior cannot be solved directly. In the present model the internal flow path is approximated as a bundle of circular tubes and the two-phase flow in a tube is regarded as annular flow. The oil amount in a component, m_{oil} , is given by Eq.(1) as the product of the oil concentration in the liquid phase, the volume of the liquid film and the liquid density, and the film thickness is determined from the balance of the shear stress, pressure and gravity acting on the liquid film, whose axial component is given by Eq.(2).

$$m_{oil} = \frac{OCR}{1 - x_{true}} 2\pi RL\delta\rho_l \quad (1)$$

$$\frac{\mu_l}{r} \frac{d}{dr} \left(r \frac{du_l}{dr} \right) = \frac{dP}{dz} + \rho_l g_z \quad (2)$$

where x_{true} is the quality including oil, R the tube radius, L the tube length, δ the film thickness, ρ_l the liquid density, μ_l the liquid viscosity, r the radius from the tube center, u_l the velocity in the film, P the pressure and g_z the gravitational acceleration in the flow direction. The velocity distribution is solved with the interfacial shear stress τ_i at the gas-liquid interface and the no-slip condition at the wall to obtain the film thickness that satisfies the given liquid flow rate, where τ_i is expressed with the gas-liquid interfacial friction factor f_i , a function of the liquid and vapor Reynolds numbers, the dimensionless film thickness and the mixture Weber number. Since existing correlations target general straight tubes, f_i was identified here from direct measurement of the oil amount, accounting for the microscopic flow inside components and the property change caused by oil solubility. The component models were connected over the cycle, where the total oil equals the charged amount, and the system OCR is obtained from the circulating oil and refrigerant flow rates.

The friction factor was identified from oil amounts measured directly in a chiller: on a test bench with R1234yf and POE oil, the chiller was isolated after steady state and purged and the oil amount was obtained from the mass difference for five conditions (refrigerant flow rate 56–114 kg/h, outlet superheat 8–27 K, OCR 1.5–8.0%). The model reproduced both the measured oil amount and the trend that the oil amount increases as the liquid velocity decreases and the superheat increases, which indicates that the identified friction factor is physically valid. The system OCR was then predicted for a specific vehicle under 82 conditions of cooling, heating and cooling with battery cooling at refrigerant flow rates of 30–160 kg/h; the RMSE was 0.39% and the coefficient of determination R^2 was 0.97 (Fig.1). The predicted breakdown showed that the OCR decreases as the oil retained in the evaporator and the pipes increases.

The model identifies, before prototyping, the operating conditions that lead to insufficient lubrication and determines the minimum oil charge that secures lubrication. Since the oil charge also affects efficiency, the model is effective for design that satisfies both reliability and efficiency. Future work includes extension to other refrigerants, oils and transient behavior.

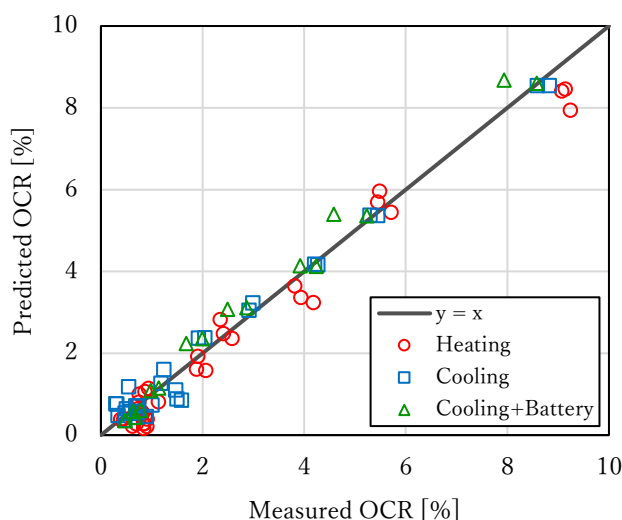


Fig.1 Measured and predicted system OCR