

Modeling Pressure Drop in Self-Circulating Phase-Change Cooling Systems for HVDC Converter Valves

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Abstract

A precise model for pressure drop is crucial for designing and ensuring the stable operation of two-phase flow cooling systems. Most current models for two-phase frictional pressure drop are created for specific conditions, which restricts their direct use in real-world scenarios of thermal management in high-voltage direct current (HVDC) converter valves. To overcome this limitation, this research develops a specialized experimental setup tailored to the features of a self-circulating phase-change cooling system used in HVDC converter valves. The pressure drop model is adjusted and then validated through experimental testing. The findings show that the predictions from the revised model closely match the experimental results, with a maximum relative error of 12% or less. This consistency offers theoretical backing and practical guidance for implementing self-circulating phase-change cooling systems in the design of HVDC converter valve cooling solutions.

Introduction

- HVDC transmission is vital for renewable energy integration
- Converter valves are key components; thermal management limits performance [4-8]
- Two-phase cooling offers >500 W/cm² heat removal [16]
- Challenges: flow instability, pressure drop oscillations, temperature non-uniformity [20-23]
- Accurate pressure drop modeling is essential for design and stability [17-19]

Theoretical Analysis

- Homogeneous equilibrium model: $\frac{dP}{dz} = \frac{2f_{lm}m^2}{D\rho_l} = \frac{2f_{lg}m^2}{D} \cdot \frac{1}{(1-x)\rho_l + x\rho_g}$
 - Separated flow model: $\Phi_l^2 = 1 + \frac{C}{X_g} + \frac{1}{X_g^2}$ $\Delta P_f = \frac{2f_{lm}}{D} \cdot \frac{G^2}{\rho_l} \cdot K \cdot L$
- the two-phase frictional pressure drop depends primarily on the square of mass flux and vapor quality, showing an approximately quadratic dependence on mass flux. In the 150 mm high heat exchanger, thermodynamic equilibrium is assumed both phases are saturated at the same temperature and pressure. Thus, thermo-physical properties are uniquely determined by pressure alone. The frictional pressure drop can therefore be expressed as a function of pressure, inlet enthalpy, and heating power, simplifying model calculations and numerical simulations.

Experimental Model

The test rig (Fig. 1) uses DGS55—a novel evaporative coolant with a boiling point of 55° C at atmospheric pressure—and consists of a return pipe, an evaporator (with a heated section), a riser, and a top-mounted condenser, forming a 1.5 m tall loop to maximize gravitational driving head. The condenser has ample capacity to maintain near-constant system pressure, and its cooling water is supplied by a precision temperature-controlled chiller to ensure repeatable boundary conditions.

Experimental conditions: Experiments were performed at 0–0.02 MPa and 20°C coolant temperature. A stepwise strategy was used: stabilize pressure via cooling water adjustment, then incrementally increase heating current under constant pressure. This leveraged the system's self-regulation, enabling pressure drop measurement and flow regime observation across varying heat inputs.

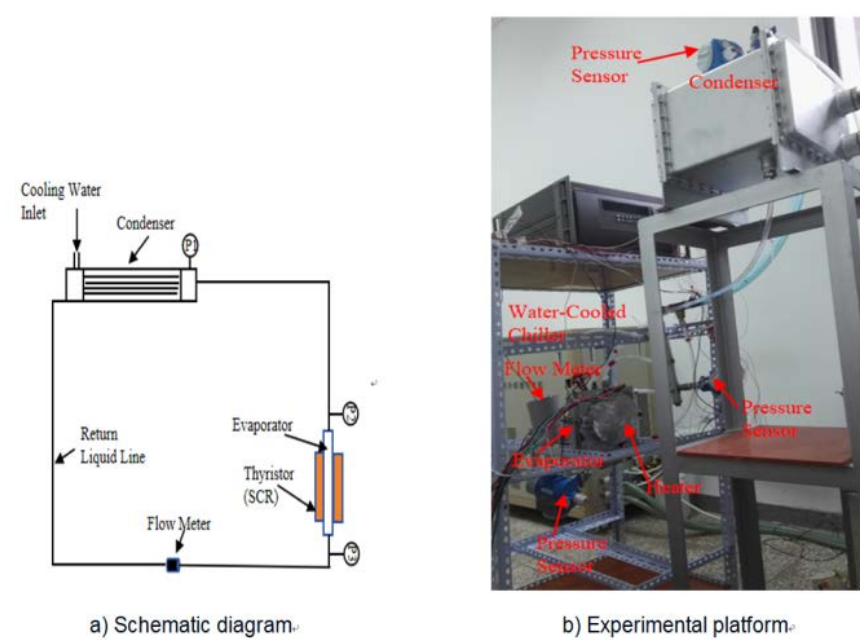


Fig. 1 Experimental platform for the self-circulating phase-change cooling system

Results and Discussion

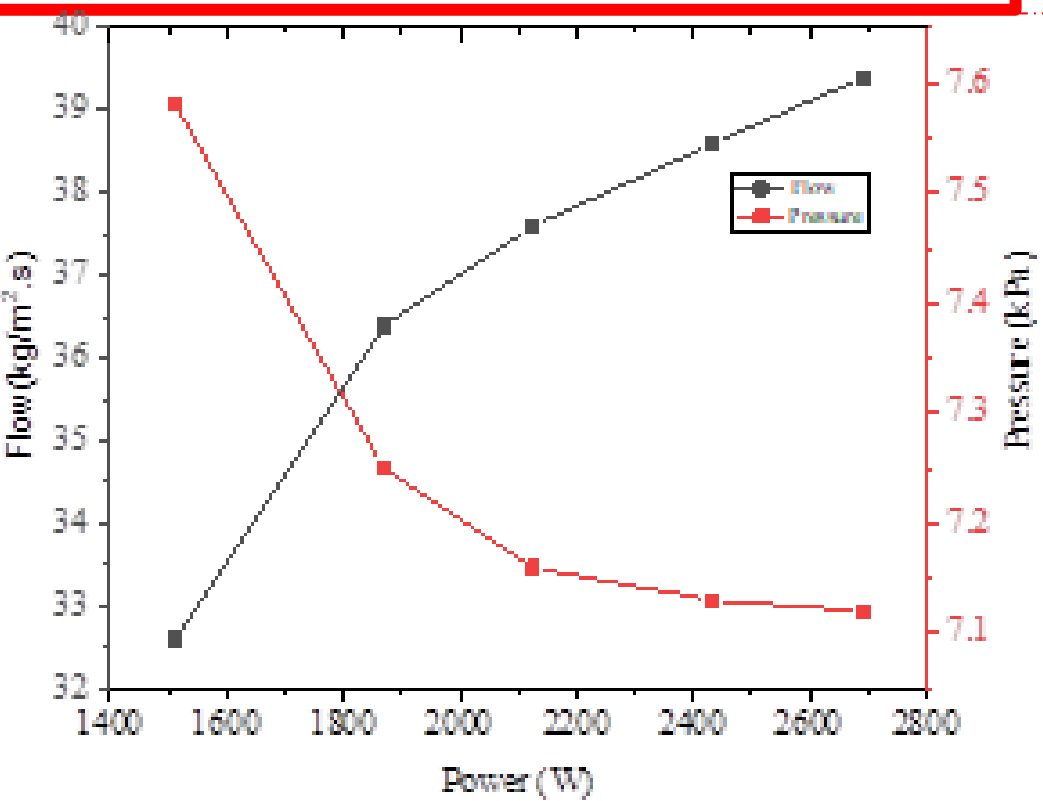


Fig.2 The evolution trends of system pressure and circulation flow rate with increasing heating power

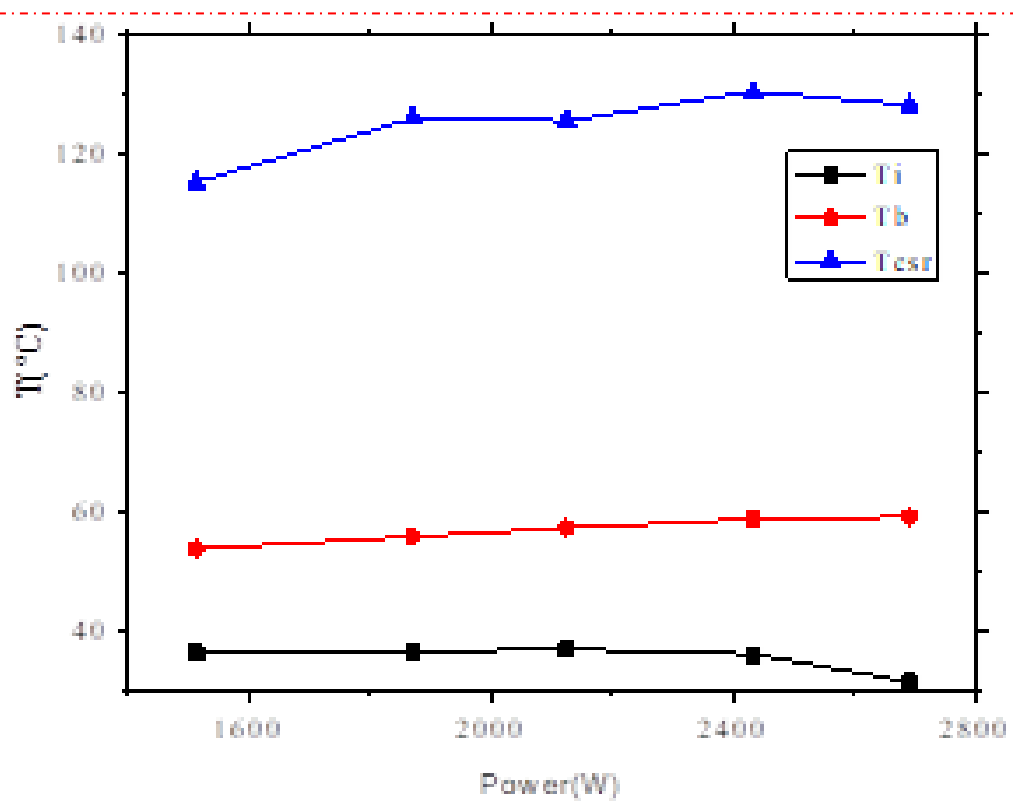


Fig.3 The variation of temperature at different locations of the heat sink as a function of power

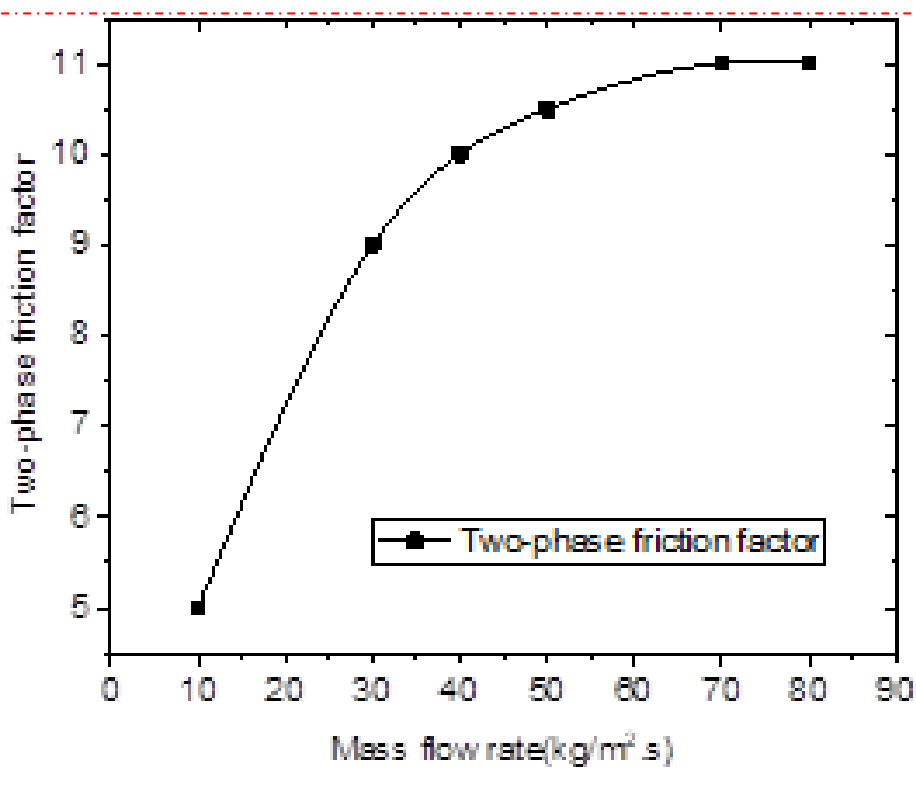


Fig.4 Fitted curve of the coefficient C

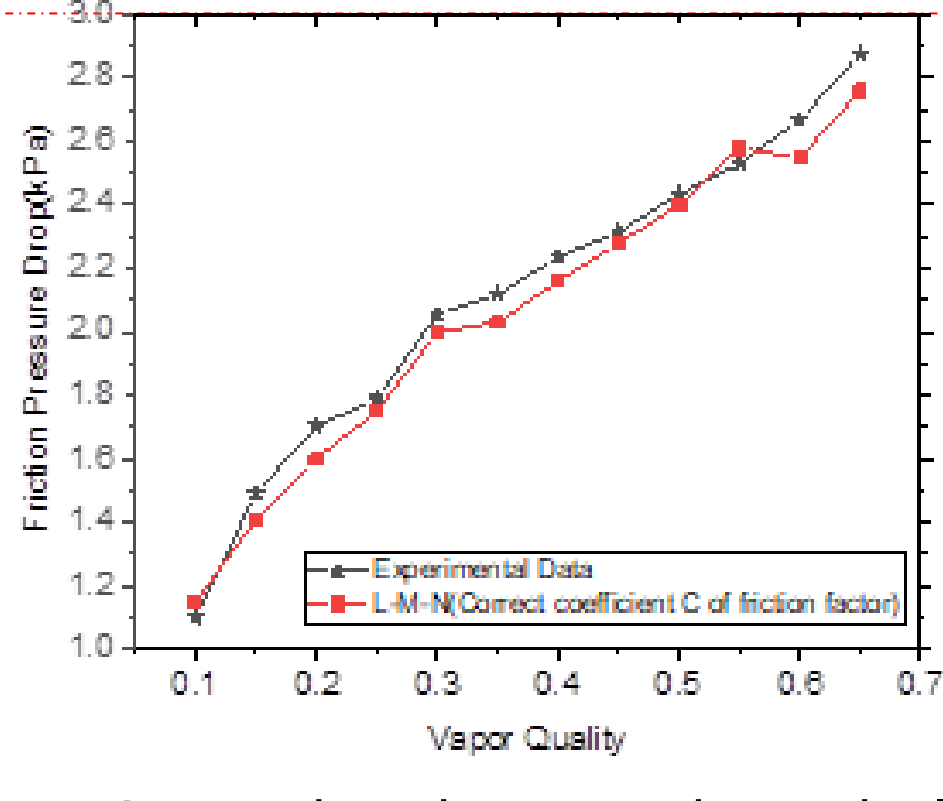


Fig. 5 Comparison between theoretical calculation and experimental results under a mass flux of 30 kg/(m²·s)

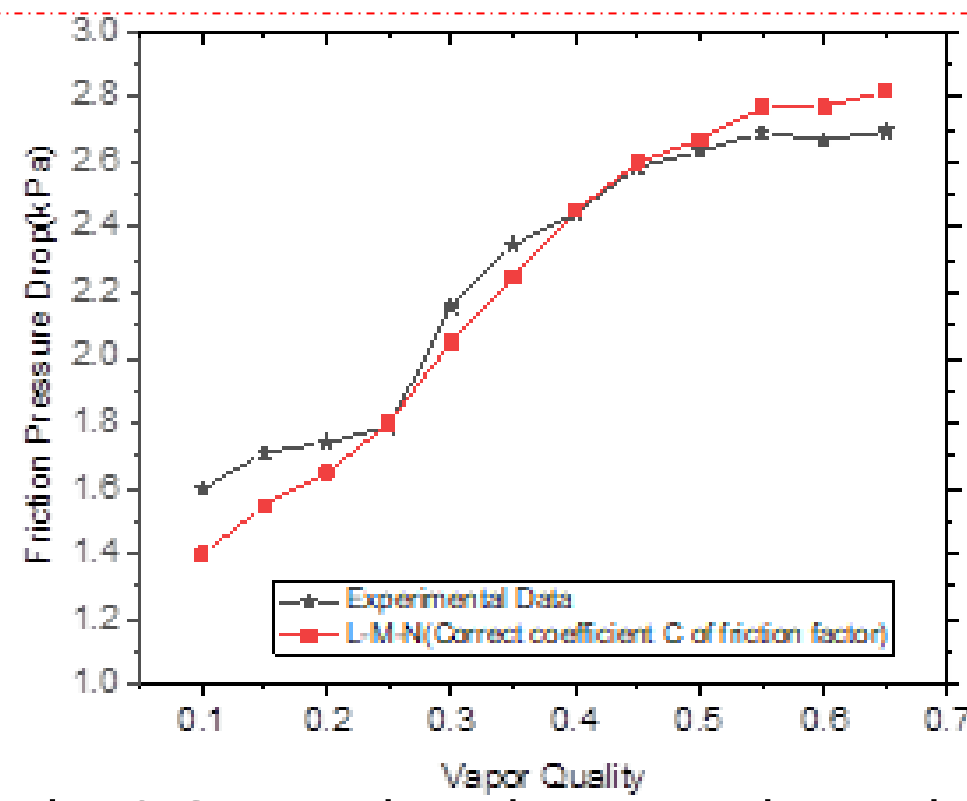


Fig. 6 Comparison between theoretical calculation and experimental results under a mass flux of 40 kg/(m²·s)

- **Figure 2** illustrates the trends in system pressure and circulation flow rate as heating power increases.
- **Figure 3** depicts the temperature variations at different heat sink locations as a function of power, where Ti represents the surface temperature at the coolant inlet, Tb denotes the surface temperature 10 mm above the heat source, and Tcsr is the surface temperature directly above the heat source.
- **Figure 4** an empirical correlation for the parameter as a function of mass flux is proposed in the present work .
- **Figure 5 and Figure 6** are respectively shown in comparison between theoretical calculation and experimental results under a mass flux of 30 kg/(m²·s) and 40 kg/(m²·s) .

Conclusion

- This study focuses **on the dimensionless C coefficient**, a critical correction parameter for frictional pressure drop calculation. Combined with two-phase flow theory and experimental data, the nonlinear variation rules of the C coefficient dependent on mass flux, void fraction and flow regime transition are revealed, and a dynamically corrected model with clear physical mechanism is established accordingly.
- Experimental results verify the prediction performance of the proposed model under typical operating conditions. At the mass flux of 30 kg/(m²·s), the mean relative error is 3.5% and the maximum error is less than 6%. For the mass flux of 40 kg/(m²·s), the mean relative error and maximum error **are 4.1% and 12%**, respectively. The proposed model presents **much higher prediction accuracy** than conventional empirical models, whose mean prediction errors are generally above 15%. The mechanistic dynamic correction method for the C coefficient effectively remedies the extrapolation failure problem commonly existing in traditional black-box empirical models.