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Development of a Machine Learning-Based Model for Cryogenic Film Boiling Flow Pattern Prediction During Transfer Line Chill-Down Operation

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The transfer of vapor-free liquid cryogen through fluid systems in low-temperature applications demands achieving thermal equilibrium between the channel wall and the flowing liquid. This transient cool-down phase, known as transfer line chill-down, poses challenges due to associated complex two-phase heat and mass transfer phenomenon. Accurate modelling of the same is necessary for optimizing cryogen usage during this phase as well as to make sure the safety of the system from severe fluid transients.
The traditional approach in predicting cryogenic flow film boiling heat transfer has relied heavily on empirical and semi-empirical correlations, which are often limited in their ability to capture the intricate non-linearities inherent in heat transfer phenomena during flow boiling. Machine learning presents a promising alternative by offering the capability to decipher complex relationships among fluid flow parameters and heat transfer. This allows for the accurate calculation of wall-fluid heat transfer coefficients, a critical aspect in optimizing cryogenic transfer line operations. Despite the success of artificial neural networks in conventional flow boiling scenarios, there exists an unexplored realm in cryogenic feed line chill-down boiling.
Available research findings have indicated that film boiling is prevalent during most of the feed line quenching process, underscoring the pivotal role of an appropriate constitutive model for the same in ensuring the accuracy of numerical models for chill-down. This study aims to pioneer a machine learning-based model tailored for chill-down film boiling heat transfer prediction. The film boiling regime in chill-down exhibits various flow patterns, including Inverted Annular Film Boiling (IAFB), Inverted Slug Film Boiling (ISFB), and Dispersed Flow Film Boiling (DFFB). Hence, one of the critical aspects in numerically solving the conjugate heat transfer during cryogenic quench flow boiling is the identification of the prevailing flow pattern and then to use appropriate wall-fluid heat transfer correlation. Building upon prior empirical correlations developed by the Cryogenic Engineering Centre IIT Kharagpur, this study explores the potential of machine learning to autonomously identify specific flow patterns during cryogenic flow film boiling, potentially involving classification problems.
Initially, an Artificial Neural Network (ANN) was selected for analysis. Following a preliminary dataset-cleaning process, various feature selection methods were employed, including Mutual Information, Maximal Information Coefficient, Principal Component Analysis (PCA), correlation matrix visualization, and decision trees. Notably, the outputs from Mutual Information and Maximal Information Coefficient exhibited consistent performance. Consequently, the ANN model training commenced utilizing features selected through these methods. The architecture comprised 15 input nodes, one hidden layer with 8 nodes utilizing the Rectified Linear Unit (ReLU) activation function, and three output nodes with SoftMax activation. This configuration yielded a training accuracy of 94.48% and a testing accuracy of 48.33%. Attempts to enhance the model by adjusting the number of hidden layers and nodes did not improve the results. Further iterations involved dataset modifications and strategies to mitigate overfitting, resulting in improved training accuracy of 97.64% and a testing accuracy of 97.79%. Subsequent attribute analysis revealed three non-significant parameters, leading to their removal and achieving a training accuracy of 95.74% and a testing accuracy of 98.51%. Subsequently, a non-dimensional dataset approach was explored, undergoing similar preprocessing steps and feature selection. Various architecture configurations were tested, with the optimal setup comprising two hidden layers with 32 and 64 nodes, respectively, resulting in a peak accuracy of 90.25%. The dataset was also utilized to train a Support Vector Machine (SVM) model using the same 15 input features as in ANN model. Basic hyperparameter tuning through GridSearchCV yielded a test accuracy of 79%.
In conclusion, this research contributes to understanding of cryogenic feed line chill-down phenomena and establishes a foundation for accurate numerical modelling based on machine learning. This study proposes an optimization tool for cryogenic transfer line operations, impacting various applications such as space technologies, LNG transport, clean energy systems, food processing, and cryosurgery. The promising results thus far indicate the potential for machine learning to revolutionize our ability to predict and optimize heat transfer in cryogenic systems.

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