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Study of Boiling Heat Transfer and Two-Phase Flows using Physics-Informed Neural Networks

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1. ABSTRACT

This work implements a physics-informed neural network (PINN) technique for evaporative phase change and other two-phase flow scenarios involving heat transfer. Initially, the case of a single gas bubble rising in a quiescent fluid was considered, wherein the PINN method achieved a maximum error of 3.6%. Evaporation studies were also performed to assess the transfer learning capabilities of the PINN algorithm, revealing a maximum PINN prediction error of 6.1%. Finally, the process of film boiling was evaluated using PINN methodology. This work serves to demonstrate that PINNs can reconcile cost-effectiveness with model accuracy for boiling problems.

2. INTRODUCTION

Since boiling heat transfer (BHT) encompasses a multitude of applications, which range from drawing heat from power-dense electronics [1] to distillation of fossil fuels [2] and evaporative cooling of solar collectors [3], improving the current understanding of BHT is essential in maintaining the current rate of technological advancement. Current simulation methods are cumbersome, resulting in design bottlenecks and a lack of reliable real-time solutions approaching the limits of system capacity [4]. Therefore, the objective of this work has been to design and test a flexible boiling heat transfer solver, which draws upon physics-informed deep learning to make accurate predictions of system behaviour in cases where limited data is available.

Accurate prediction of boiling behaviour is only possible with a detailed understanding of bubble dynamics [5]. Accordingly, the scope of this work encompassed other two-phase flow cases, generalisable across many areas within fluid dynamics. This included the prediction of bubble motion in both isothermal and temperature-dependent domains, where the effects of the bubble wake on surface heat transfer were studied. Models were regularly employed to make inverse predictions (i.e. predictions were made without supplying observational data) to demonstrate the power of PINNs as a method of accelerating parametric studies and preparing them for implementation as part of real-time control systems, which remains relevant for many domains within fluid mechanics.

The present work applies advances in PINN methodology to the process of phase change by sequentially growing a portfolio of two-phase and evaporative case studies. In doing so, a robust solver has been created, which can be applied to many areas of fluid mechanics to accelerate the design process and reduce the required safety margin in both research and industrial settings.

3. METHDOLOGY

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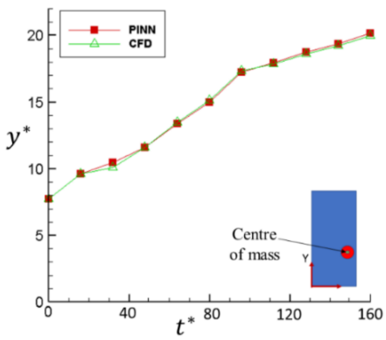
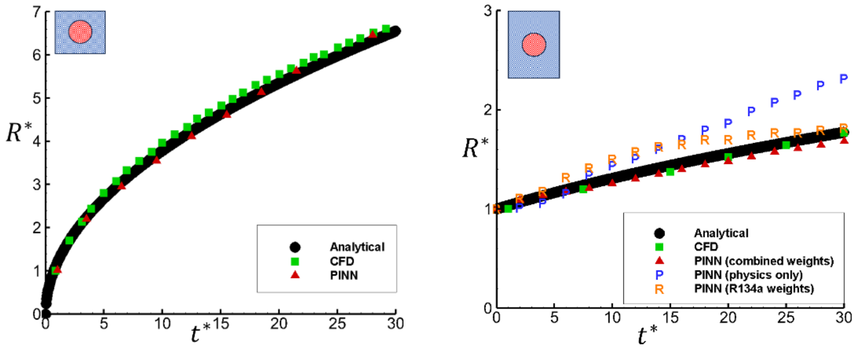
PINN techniques rely on a selection of partial differential equations (PDEs) which enable comprehensive predictions of system behaviour when solved simultaneously. This work validated the accuracy of PINN methods when tasked with solving the Navier-Stokes equation, the transient energy equation, the Volume of Fluid (VOF) colour function and the Hardt & Wondra mass transfer model. In this work, it was found that a sequential (ensemble) architecture was most effective at making flexible and reliable predictions based on limited observed data since the loss landscape was transformed from a global problem to one where significantly fewer loss terms were active at any one time. For all cases, time was made dimensionless such that $t^* = (t/(L/U))$. Lengths were also made dimensionless such that $y^* = y/y_0$ and $R^* = R/R_0$

4. RESULTS

For the rising bubble in a quiescent domain, the PINN algorithm performed admirably. It was able to infer the zigzag rise of the bubble and the subsequent effect of the bubble trajectory on the temperature field. Positional error peaked at 3.6% (Fig. 1). The temperature field was represented with a maximum discrepancy of just 1.5% in the near-field region and only 7% overall throughout the rise of the bubble.

Two forward problems were investigated for evaporation of a spherical bubble in a superheated liquid. Additionally, an extended inverse study was performed, within which the transfer learning capabilities of the PINN method were assessed. The error produced by the forward problem peaked at a lower value than the reference CFD data at 3.6% (vs 4.47% for CFD). For the inverse study, a prewarmed network was able to accurately predict the evaporation rate of FC-72, an unobserved fluid to within 6.1% of the true analytical solution and within 1.4% of the accuracy attained by the reference CFD method.





(a) Water vapour growth

(b) FC-72 Vapour growth (inverse problem)

Figure 1: Predictions of bubble centre of mass height over time for CFD and PINN for a bubble rising in a domain with a hot wall.

Figure 2: Quantitative comparison of PINN prediction against analytical solution and the CFD-generated solution of **(a)** a water vapour bubble, **(b)** and an FC-72 vapour bubble made using PDEs alone, R-134a weights/biases, and *combined* Water-R-134a weights/biases against analytical solution and an unobserved CFD solution of FC-72 vapour bubble growth.

5. CONCLUSIONS

This work is novel in its application of PINNs to boiling heat transfer, which promises to augment the implementation of real-time system control to enable increased safety and efficiency of two-phase systems in the presence of complex physics.

The proposed PINN method was evaluated against CFD reference data and analytical solutions, where available. The forward problem PINN predictions for evaporation of water-to-water vapour produced a peak error of 3.6% which bettered the the traditional CFD reference solution (4.47% error).

The major highlight of this work is the extended inference study, which demonstrated the resilience of PINN in accurately determining the evaporation process and, consequently, showed PINN could be made agnostic to simulation properties in the context of evaporation. Inferences of FC-72 bubble evaporation were made with errors peaking at just 6.1% compared to the relevant analytical solution. This disparity was within 1.4% of the solution produced by the traditional CFD method.

In future work, the authors intend to utilise this PINN algorithm to explore the boiling process at high levels of heat flux. At a fundamental level, this will enhance knowledge of boiling heat transfer. However, continued fundamental studies also serve to increase the understanding of PINN advantages and limitations, in preparation for implementation as part of a real-time control system. In systems which rely on phase change, the implementation of PINN as a real-time control method would have profound implications by significantly increasing the heat transfer efficiency, since information provided by sensing locations may be used to infer a more complete picture of system behaviour.

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