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1. Introduction

Multiphase fluid systems undergoing thermal convection are frequently encountered in industry and nature, from boilers and condensers to cloud and atmospheric dynamics. The prevalence of such systems has prompted interest in understanding the complex interaction between phase change and thermal convection and, particularly, how phase change affects the global properties of the flow. The standard and well-studied Rayleigh–Bénard (RB) cell [1]–[4] has been employed in recent numerical and experimental works to address questions about cloud formation in moist convection [5] and heat transport in the boiling process [6, 7]. Experiments performed on ethane near its boiling point by Zhong *et al* [7] showed a significant enhancement of heat transport compared to single-phase transport, consistent with the numerical results from simulations of water near its boiling point performed by Oresta *et al* [6].

Here, we perform simulations of boiling in a cylindrical RB cell to gain further insight into how the phase change can modify the velocity and temperature fields, and turbulence level in thermal convection. As in single phase RB convection, the dynamics are determined by the strength of the thermal forcing (the Rayleigh number) and the ratio of the kinematic viscosity to thermal diffusivity (the Prandtl number) [1]–[4]. The global response of the system is measured via the total heat transport through the cell (the Nusselt number, Nu) and the turbulence intensity (the Reynolds number, Re). For boiling, a critical additional parameter governing the heat transfer is the Jakob number, the ratio of the sensible heat to the latent heat of vaporization, Ja , which we vary to explore the different ways the phase change affects the response of the system.

When vapor bubbles form in a convecting liquid, it is not *a priori* clear how the velocity field and turbulence intensity will be modified. The dispersed bubbles have complex thermal and mechanical interactions with the liquid phase, see e.g. [8]–[17]. On the one hand, the density contrast between the liquid and vapor will induce motion due to buoyancy, but, on the other hand, the phase change from liquid to vapor removes energy from the liquid phase. It was proposed in [6], which focused on the physics of heat transfer in multiphase RB convection, that destabilization due to buoyancy dominates over stabilization due to thermal smoothing in most situations. In this paper, that idea is directly checked through calculation of the Reynolds number, with and without the thermal and mechanical feedback from the bubble on the flow.

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described in Table 1. The design and analysis of CCD runs were done using the Minitab® release 14.1 software package [27].

Specimen codes in Table 1 consist of a number following M, in which the first two digits demonstrate f_s of the space holder and the second two digits represent the corresponding d_s . Each experiment is repeated five times for reproducibility testing and the measurement of the experimental error.


2.3. Characterization

2.3.1. X-ray Computed Tomography (XCT)

In recent years, X-ray or MRI techniques have allowed the study of large representative volume elements of micro-structured materials at micrometer resolutions [28,29]. In this study, a high resolution XCT apparatus [30] is used to obtain 3D images of the samples. Our tomography setup is able to produce 3D images with a spatial resolution (voxel size) of 8.1 μm . The 3D pore-solid structure of all thirteen copper foam samples studied in this work has been

From an engineering perspective, it is important to understand the effect of manufacturing parameters on the mechanical strength of the produced foams. To investigate this, we use the finite-element method (FEM) in order to estimate the elastic properties of the foam samples. The FEM technique has been used extensively in materials science for simulating the mechanical properties of micro-structured materials, producing excellent agreement with experimental data of e.g. cellular solids and rock samples [19–21,33,34]. Our implementation of FEM uses a variation formulation of the linear elastic equations and finds the solution by minimizing the elastic energy using a fast conjugate gradient method [35]. We use a voxel based meshing scheme that meshes the segmented 3D datasets of foam samples into regular cubic finite elements. Next, a strain is applied to the meshed dataset, with the average stress and the average elastic energy giving the effective elastic modulus. It's noteworthy to mention that initial bulk and shear moduli of 140 GPa and 48 GPa (Young's modulus of 69 GPa) were assigned to the solid matrix (copper) phase [20].

684



3.1. Image based relative density

Eq. (1) presents the ANOVA results for the foams' average relative density as a fitted regression model with the highest values of R^2 . The values of R^2 and P indicate the quality of the model while

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cylinder pressure feedback have been proposed [12]. Most approaches that have previously been proposed require statistics over a large number of cycles, which defeats the purpose of trying to reduce the time delay in the feedback system. For example, it has been found that, using the indicated mean effective pressure (Imep), up to 300 engine cycles are required to achieve acceptable repeatability and accuracy [3]. Tunest (al, Lee, Wilcutts, and Hedrick (2000) presents an ad hoc attempt at higher bandwidth feedback using cylinder pressure. This paper

develops a method to estimate the AFR in an SI engine from cylinder pressure measurements [9]. The method is developed from a well-established empirical model for the dependence of laminar flame speed on temperature, pressure, and AFR, and relates this model to the heat-release rate during the rapid burn phase, which is obtained from the cylinder-pressure-based net heat release profile. Since the

actual flame speed in an SI engine depends on the turbulence intensity, a turbulence model also has to be included. This model includes a simple turbulence model implicitly, by assuming that the turbulence intensity is a function of engine speed [1]. An AFR estimator which is able to estimate cylinder AFR from cylinder pressure measurements over a wide range of operating points is developed. The variance of an individual cycle estimate is very high due to the random nature of the amount of residual gas in the cylinder, as well as the turbulent flow field which will cause the flame development to be different from cycle to cycle. Cycle-averaged AFR estimates show an RMS error of only 4.1% though.

2. REVIEW OF THE CONCEPTS OF FLAME AND FLAME SPEED The following section is a review of the concepts of flame and flame speed, and is included for completeness. The presentation is largely based on Heywood (1988) [1].

2.1. flame definition A flame is a combustion reaction which propagates sub sonically through space. For motion of the reaction zone to be well-defined, it is assumed that the thickness of the reaction zone is small compared to the dimensions of the space it is confined to. Propagation of the reaction zone refers to its motion relative to the unburned gas ahead of it, and thus a propagating flame can very well be stationary with respect to the observer. Two different classes of flames can be distinguished based on where the mixing of fuel and oxidizer (air) takes place. If fuel and oxidizer are uniformly mixed when entering the reaction zone, a premixed flame results. A diffusion flame results if fuel and oxidizer have to mix as the reaction is taking place. Similarly, flames can be characterized based on the gas flow characteristics in the reaction zone. Flames can be either laminar (stream lined flow), or turbulent (vortex motion). Flames can be classified as unsteady or steady depending on whether their overall motion or structure change with time or not. Finally, the initial phase of the fuel, when it enters

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