Complete Transient Droplet Evaporation Modelling: Deviation from the d^2 Law under Cryogenic Conditions

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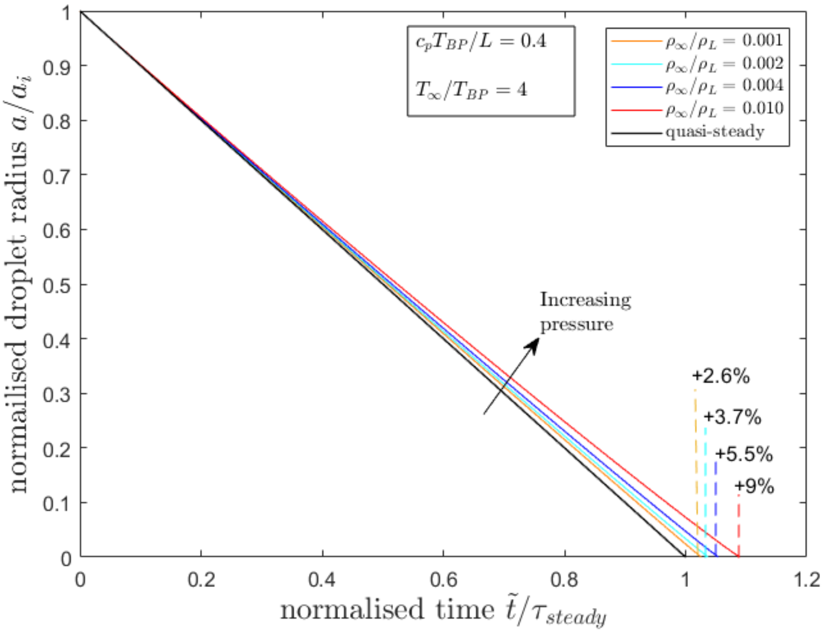
The study of evaporation is essential for many practical applications including spray cooling, power generation, combustion, medical treatments and cosmetics. Cryogenic droplets in particular are of interest when rapid and/or sub-ambient cooling is desired. Cryogens such as liquid nitrogen [1]–[3], liquid hydrogen [4]–[6] and liquefied natural gas [7]–[10] are of increasing interest in power generation cycles where droplet evaporation characteristics have a significant effect on performance in terms of fuel (or cryogen) consumption.

The evaporation of an isolated droplet in an infinite, quiescent gaseous medium is a foundational problem in droplet evaporation yet the behaviour of the full solution is yet to be adequately characterised. An often-used simplification is full quasi-steadiness where both the liquid and gas phase are considered quasi-steady. This results in the well-known d^2 law [11]. Deviations from the d^2 law can be caused by the droplet heating or cooling to the steady “wet-bulb” temperature or by transient heat and mass transfer in the gas phase surrounding the droplet. The effect of liquid phase transients is well understood [12] as it applies to ‘conventional’ droplets which typically heat up upon injection to a hot gas (e.g. fuel injection to combustion chamber). Liquid phase transients are often less significant in cryogenic applications and gas phase transients are currently not well understood.

We present full numerical solutions to heat and mass transfer equations governing the transient droplet evaporation problem and characterise the effects of liquid and gas phase transients in a generalised dimensionless form. The governing physics is not confined to cryogenic applications but the low boiling point and initial droplet temperatures close to boiling lead to different considerations compared to other evaporating fluids. Novel results include characterising self-insulating behaviour of droplets towards the end of droplet lifetime causing a slowing of evaporation rate as shown in the below Figure. We find the droplet surface heat flux (normalised) is not constant as predicted under fully quasi-steady assumptions. When a variable droplet radius is considered the surface heat flux does not converge to the steady value but diverges towards end of life. This effect is more pronounced for ‘fast’ evaporating droplets, where there is a large ambient temperature compared to the fluids boiling point, the latent heat of vaporisation is small, and the liquid density is small. Predictions of this behaviour should measurable for ‘small’ (low Froude number) cryogenic droplets evaporating under elevated pressures. This is an area for future development.



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