Advances in phase-field modelling of laser flash experiments

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During nuclear reactor operation at very high power, the centreline of a nuclear fuel element may reach very high temperatures close or even above the melting point. Such conditions can occur in fast reactor fuel during normal operation or light-water reactor fuel during power transients. In the latter case, the possibility of centerline melting is enhanced if the fuel element has defected, in which case the coolant may contact the UO_2 and oxidize it to UO_{2+x} which exhibits reduced thermal conductivity and a lower incipient melting point with non-congruent melting. Good understanding of the high temperature behaviour of nuclear fuel is therefore important for ensuring its safe and efficient operation.

A model of the high temperatures behavior of the nuclear fuel has been developed based on the phase-field approach, which accounts for non-congruent phase change in a simple and robust fashion. The model is derived using the theory of irreversible process, which links kinetic and thermodynamic treatments on a fundamental level. The derivation naturally includes phase stability analysis (Gibbs energy minimization) as well as cross-effects between heat and mass transport that are observed in materials under extreme conditions such as nuclear fuel. The later point is important as thermodiffusion causes the redistribution of species such as plutonium and oxygen in the very large temperature gradients typical of nuclear fuel in the current generation of commercial reactors, which are and expected to be larger in fast reactor design.

The versatile and general development of this model allows for its ready application to a variety of experiments. The current work has been applied to the analysis of laser flash experiments on the melting behaviour of UO_{2+x} and UO_2-PuO_2, laser heating experiments simulating high power conditions, direct electrical heating experiments on spent fuel and in-reactor irradiation of defected fuel elements. It is also able to be integrated into other fuel performance and oxidation models in order to extend their range of applicability into situations where melting may occur.

This work therefore details the fundamentally based development of a model which links transport phenomena to thermodynamic analysis in a comprehensive and self-consistent manner. The result has been employed in the analysis of the material properties of nuclear fuel under extreme conditions, and the application of these properties to safety analysis for nuclear reactor operation.