# Version 2.0 - laserbeamFoam: Laser Ray-Tracing and Thermally Induced State Transition Simulation Toolkit

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## Abstract

In this update to the **laserbeamFoam** toolbox, a multi-component version of the solver is included with pair-wise Fickian Diffusion between selected component pairs. This new solver, **multiComponentlaserbeamFoam**, captures the multi-component nature of mixing between alloys, and as-such could be used to simulate dissimilar laser joining processes, and dissiimilar laser-powder-bed additive manufacturing, among others. Additionally a multi-laser version of the original **laserbeamFoam** solver is included (**arraylaserbeamFoam**) that can simulate N incident laser sources on a metallic substrate, where the direction, velocity, and other laser characteristics can be specified independently. In both these solvers, as in the original **laserbeamFoam** solver, the phenomenological recoil pressure treatment is used, as opposed to the full volumetric dilation treatment, for computational tractability.

*Keywords:* thermal-fluid-dynamics , multi-component , laser-deposition

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## Metadata

| Nr. | Code metadata description | Please fill in this column |
|---|---|---|
| C1 | Current code version | V2.0 |
| C2 | Permanent link to code/repository used for this code version | For example: `https://github.com/micmog/LaserbeamFoam` |
| C3 | Code Ocean compute capsule | No |
| C4 | Legal Code License | GNU GPL V3 |
| C5 | Code versioning system used | git |
| C6 | Software code languages, tools, and services used | C++, C, MPI |
| C7 | Compilation requirements, operating environments & dependencies | OpenFOAM-10 |
| C8 | If available Link to developer documentation/manual | `https://github.com/micmog/LaserbeamFoam/README` |
| C9 | Support email for questions | tom.flint@manchester.ac.uk<br>philip.cardiff@ucd.ie |

## 1. Description of the software-update

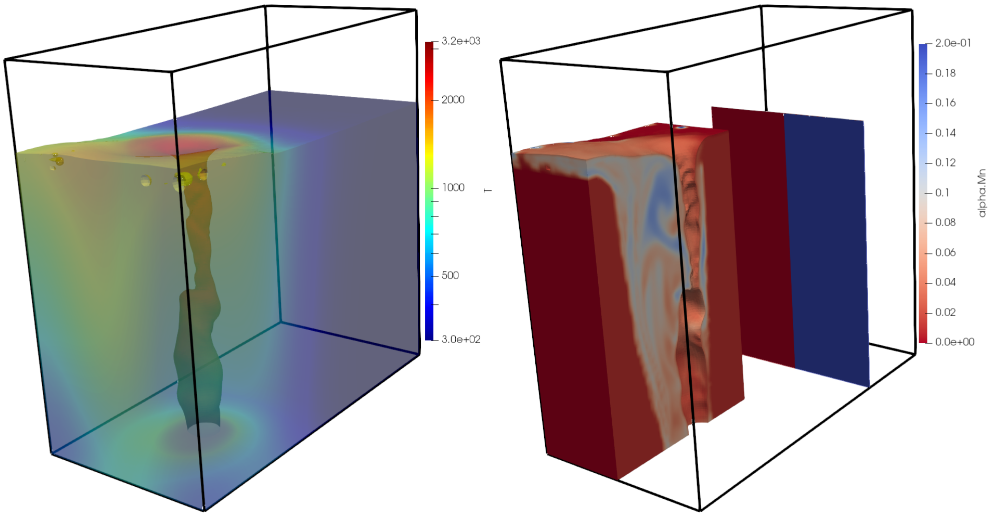
The solvers included in the **laserbeamFoam** toolbox utilise the phenomenological recoil pressure approach to capture the vapourisation state transition. Higher fidelity approaches, that fully capture the multi-component volumetric dilation due to vapourisation/condensation exist, and have been published elsewhere [1, 2, 3, 4]. These higher fidelity approaches more robustly describe the momentum contribution due to vapourisation/condensation events that operate to stabilise/destabilise thermo-capillaries (keyholes) generated during high energy density laser-substrate interactions; and also permit the simulation of interesting phenomena such as preferential element loss. However, these higher fidelity approaches are incredibly computationally expensive, as the vapourisation events generate high velocity regions in the domain that must be resolved. It has been found by the present authors, that for scenarios not dominated by vapourisation, or for scenarios where not all of the physics need be captured, this phenomenological approach is suitable [5, 6]. The additional solvers included with this update all solve the same conservation of energy, and momentum equations described elsewhere [7]. All solvers account for surface tension, temperature dependence of surface tension, buoyancy forces and momentum damping due to solidification. The two new solvers, generalise the original **laserbeamFoam** solver to multiple laser sources (**arraylaserbeamFoam**) and multi-component metallic substrates (**multiComponentlaserbeamFoam**).

### *1.1. multiComponentlaserbeamFoam*

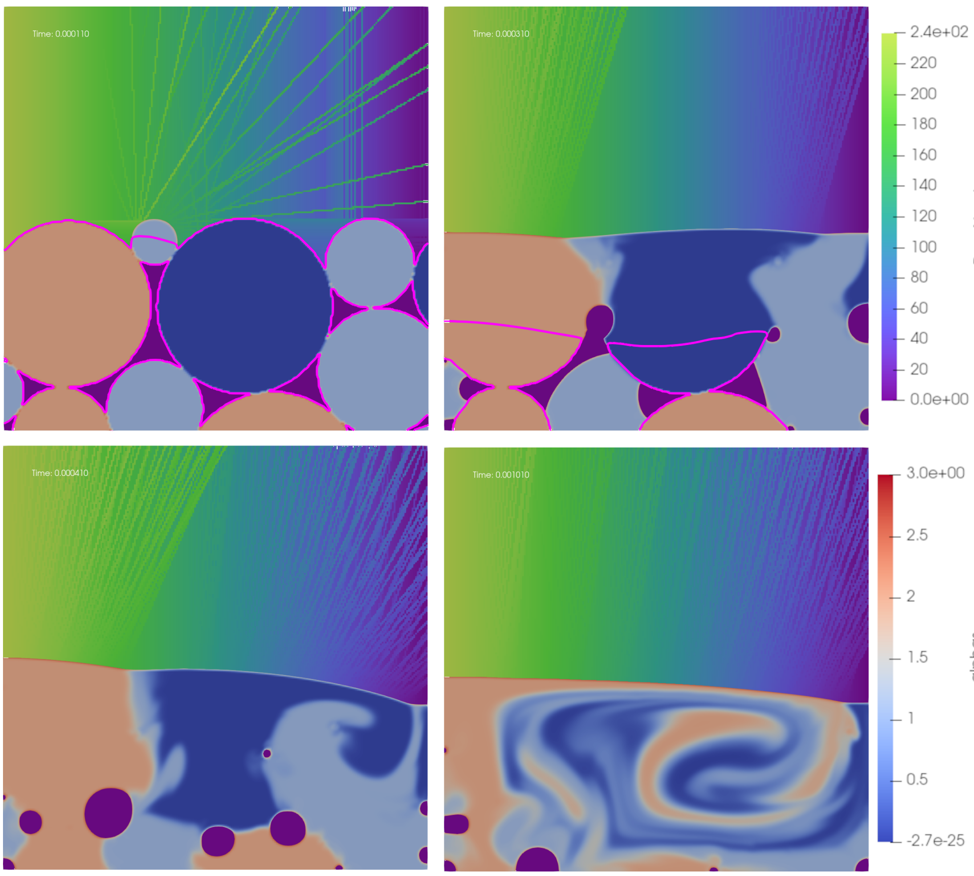
The **multiComponentlaserbeamFoam** solver assumes that there are M+1 component species in the domain, where M is the number of metallic, miscible, components and the final component is a gaseous, immiscible species. As in the original **laserbeamFoam**, we use the volume of fluid method. Equation 1 shows the volume fraction equation that is solved per-component in the domain.

$$\frac{\partial\left(\alpha_k\right)}{\partial t}+\nabla\cdot(\boldsymbol{U}\alpha_k)+\sum_{k}^{N}\sum_{l\neq k}^{N}\nabla.\left(U_c\alpha_k\alpha_l\right)=\sum_{k}^{N}\sum_{l\neq k}^{N}\nabla.\left(\epsilon_1 D_{kl}\left(\alpha_k\nabla\alpha_l-\alpha_l\nabla\alpha_k\right)\right). \tag{1}$$

In Equation 1, $U_c$ is the interface compression term, that is applied between the gaseous and metallic components in the domain (applied along the normal vector to the interface); see elsewhere for additional details [8]. $D_{kl}$ are the pair-wise diffusive terms, all other terms have the same meaning as in the original **laserbeamFoam** publication. Naturally, interface compression should be applied between the gas and metallic components and diffusion coefficients be applied between metallic components in the mixture. The implementation of the diffusion model has been validated against analytical solutions for binary diffusion. The multi-component solver uses a phenomenological recoil pressure approach with parameters in this assumed to be weighted averages of the pure component values, weighted by the volume fraction of each component in a given computational cell.




(a) Example of **multiComponentlaserbeamFoam** applied to simulate the laser joining of two dissimilar metallic substrates where there are three metallic components present in the domain that mix in the liquid state. The fields *alpha.Ni* and *T* correspond to the Nickel volume fraction and temperature respectively.



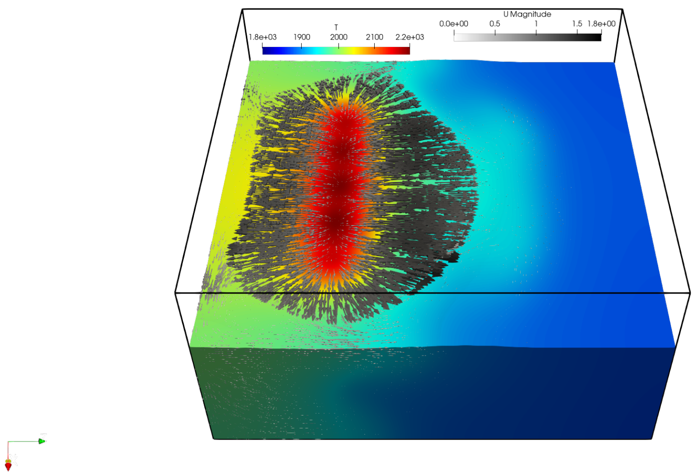

(b) Example of **multiComponentlaserbeamFoam** applied to simulate the melting of a dissimilar powder-bed substrate with three metallic components that melt then mix together. The fields *alphas* and *Ray_Number* correspond to the average component indicator fields and discretised beam numbers .respectively

Figure 1: Example output results from the **multiComponentlaserbeamFoam** solver showing the advective and diffusive mixing in the liquid state of dissimilar metallic substrates.

Figure 2 shows typical results obtained from the **multiComponent-laserbeamFoam** solver; for a dissimilar laser welding scenario and for a sissimilar powder bed scenario. In both cases the effect of diffusion can be seen through the mixing within the molten metallic volume.

### *1.2. arraylaserbeamFoam*

This solver generalises the original **laserbeamFoam** solver to account for N laser sources, by creating a class for the laser object in the software. This means the laser parameters for each source can be set independently.




(a) Example output from the **arraylaserbeamFoam** solver where 5 laser sources, in a linear configuration are incident on a metallic-sunstrate

Figure 2: Example output results from the **arraylaserbeamFoam** solver.

Figure 2 shows the velocity and temperature distribution in a domain wherer 5 laser sources are directed onto a metallic substrate; generating complex surface flows mainly driven by the temperature dependence of the surface tension.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