Reduced finite-volume model for the fast numerical calculation of the fluid flow in the melt pool in laser beam welding

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Abstract. In this paper we propose a reduced two-dimensional finite-volume model for the fast calculation of the melt flow. This model was used to determine the influence of the welding speed, viscosity in the melt and vapour flow inside of the keyhole on the fluid flow field, the temperature distribution, and the resulting weld-pool geometry for laser beam welding of aluminium. The reduced computational time resulting from this approach allows the fast qualitative investigation of different aspects of the melt flow over a wide range of parameters. It was found that the effect of viscosity within the melt is more pronounced for lower welding speeds whereas the effect of friction at the keyhole walls is more pronounced for higher welding speeds. The weld-pool geometry mainly depends on the welding speed.

1. Introduction
The fluid flow in the weld pool is related to many characteristics of the laser beam welding process such as the temperature distribution [1], quality aspects like humping [2], and the distribution of alloying elements [3, 4]. Due to the interdependence of pressure, velocity and temperature and the varying boundary conditions like the time-dependent shape of the keyhole, a direct analytical calculation is only possible to a limited extent. Numerical models have long proven to be a valuable tool for gaining insight into the physical processes involved in laser beam welding [1, 5–11]. Recently impressive multi-physical models have been shown, including multiple reflection models for the absorptance of the laser beam [12, 13], 3D-flow calculation and free surface flow [6, 7, 14–16], evaporation models [6, 7, 14–16] and models for the calculation of the resulting microstruct ure [17–20] and solidification cracking [21–23].

While these models give great insight into the welding process, the large number of influencing variables makes it difficult to determine their impact on the process result. Additionally, new beam shaping technologies [24–26] offer the potential to influence the shape of the keyhole. Knowledge about the interaction between keyhole and melt is therefore needed for adapting the suitable strategy for each process. In the present paper, we propose a reduced two-dimensional finite-volume model with the intention that the reduced complexity and the reduced simulation time resulting from this approach allow the fast qualitative investigation of different aspects of the melt flow over a wide range of parameters. With this model, the influence of viscosity in the melt and of friction at the wall of the keyhole is analysed and compared for different welding speeds.
2. Numerical Model

The reduced numerical model was implemented for the case of a moving sheet under a static laser beam using the open source software OpenFOAM® v2012 (ESI-OpenCFD) [27, 28]. For each time step at first the basic heat conduction equation [29–31]

$$\frac{\partial(\rho c_p T)}{\partial t} + \nabla \cdot (\rho u c_p T) = \nabla \cdot (\lambda_{th} \cdot \nabla T) + S_h$$

(1)

is solved, where $T$ is the temperature, $t$ is the process time, $u$ is the vector of the velocity, $\lambda_{th}$ is the heat conductivity, $c_p$ is the specific heat capacity and $\rho$ is the density. As introduced by Rösler and Brüggemann [30], the equation is extended by the source term

$$S_h = -\Delta h_f \left(4 \cdot \exp \left( \frac{4(T - T_m)}{T_{\text{liquid}} - T_{\text{solid}}} \right)^2 \right) \frac{\partial T}{\partial t}$$

(2)

in order to account for the latent heat $\Delta h_f$ of the phase change between liquid and solid, where $T_{\text{liquid}}$ is the liquidus temperature, $T_{\text{solid}}$ is the solidus temperature and $T_m$ is the average of liquidus and solidus temperature.

This calculation of the temperature distribution is coupled to the calculation of the melt flow, which is based on the solver icoFoam from OpenFOAM®. With this the incompressible laminar Navier-Stokes equations are solved for each discrete time step by applying the PISO algorithm [32–34]. In order to distinguish between the fluid flow in the weld pool and the constant velocity of the solid sheet, which is equal to the welding speed, a source term

$$S_m = -\frac{C(1 - (1 - f_s))^2}{(1 - f_s)^3 + b} \cdot u_{rel}$$

(3)

based on the Darcy law for the flow in porous media is added to the momentum equation

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u - \nabla \cdot (\nu \nabla u) = -\nabla p + S_m$$

(4)

as proposed in [35], where $C$ is the mushy zone constant, $b$ is a small value which is introduced to avoid division by zero, $u_{rel}$ describes the velocity vector relative to the feed rate of the solid part, $\nu$ is the kinematic viscosity, $p$ is the pressure and $f_s$ is the solid fraction which describes the phase state. A solid fraction of $f_s = 0$ represents the liquid state and a solid fraction of $f_s = 1$ represents the solid state. During the solidification between $T_{\text{liquid}}$ and $T_{\text{solid}}$ the solid fraction increases from $f_s = 0$ to $f_s = 1$. In this model, the course of this increase of the solid fraction is described by a sigmoid function according to [30]. During melting the decrease of the solid fraction from $f_s = 1$ to $f_s = 0$ is described by the same sigmoid function.

As shown by Rösler and Brüggemann [8], for each material property one value for the solid state $\beta_{\text{solid}}$ and one for the liquid state $\beta_{\text{liquid}}$ is specified and $\beta$ is calculated as

$$\beta = f_s \cdot \beta_{\text{solid}} + (1 - f_s) \cdot \beta_{\text{liquid}}.$$  

(5)

For each state the material parameters are considered as constant values. In order to drastically reduce the simulation time, the model is applied to a two-dimensional mesh. It is assumed that the process is symmetric with respect to the weld’s centreline. In order to model this, the rectangular calculation area is limited to one half of the weld seam and a symmetry boundary condition is applied. To further reduce the complexity, the keyhole is assumed to be of a constant cylindrical shape. This is represented in the mesh by a constant geometrical boundary with a cylindrical shape with a diameter equal to the beam diameter on the surface $d_l$. Different boundary conditions can be assigned to the front and the back of the keyhole. In order to account for the feed rate of the sheet, a constant velocity is applied at the boundary of the mesh with constant temperature $T_{\text{amb}}$ and $f_s = 1$. This results in the simulation of a sheet
which is moved at constant feed rate \( u_{\text{weld}} \), while the laser beam is resting with constant position and orientation. The calculation area with all applied boundary conditions is shown in Figure 1. The coordinate system is placed at the centre of the keyhole with \( x \) in direction of the sheet’s feed rate and \( y \) transverse to the feed rate. The detail view in Figure 1 shows the keyhole and a representation of the local mesh.

\[ \dot{Q}_i = -\lambda_{\text{th}} \cdot A_i \cdot \nabla T_{\text{rad}} \]  

where \( A_i \) is the interface area at the keyhole wall for each cell and \( \nabla T_{\text{rad}} \) is the corresponding radial temperature gradient. Consequently, the total absorbed power per penetration depth \( P_{\text{depth}} = \sum \dot{Q}_i \) varies for each simulated case and is provided with the results. At the keyhole’s rear (blue in Figure 1) a \textit{zeroGradient} boundary condition is applied for the temperature field. In order to gain insight into the interaction of the melt flow with the wall of the keyhole, the boundary conditions for the tangential flow \( u_{\text{tan}} \) at the wall were varied during the investigations. No mass transfer through the keyhole wall was assumed e.g. \( u_{\text{rad}} = 0 \, \text{m/s} \) for all cases.

The model can be considered as the top layer of a deep penetration process. With this model, laser beam welding of the aluminium alloy AA6016 was investigated. The material properties were chosen as listed in Table 1. In order to achieve faster convergence of the solution for all cases, at first the temperature field with a homogenous flow field with \( u = u_{\text{weld}} \) was calculated. This allowed for a
convergence to a steady state flow in the subsequent flow simulation after \( t = 0.1 \) s of simulated process time.

Due to the two-dimensional approach and the restriction of influencing factors, the model enables reduced simulation times. This provides the possibility to vary a large number of process parameters in short time.

### Table 1. Constant properties used in the simulation of welding of aluminium alloy AA6016 [37, 38].

| Parameter                          | Unit       | Value  |
|------------------------------------|------------|--------|
| Ambient temperature \( T_{\text{amb}} \) | °C         | 20     |
| Solidus temperature \( T_{\text{solid}} \) | °C         | 610    |
| Liquidus temperature \( T_{\text{liquid}} \) | °C         | 660    |
| Evaporation temperature \( T_{\text{evap}} \) | °C         | 2450   |
| Enthalpy of fusion \( \Delta h_f \) | J/kg       | 390000 |
| Heat capacity (solid) \( c_p,\text{solid} \) | J/(kg K)  | 900    |
| Heat capacity (liquid) \( c_p,\text{liquid} \) | J/(kg K)  | 1126   |
| Thermal conductivity (solid) \( \lambda_{\text{th, solid}} \) | W/(m K)   | 210    |
| Thermal conductivity (liquid) \( \lambda_{\text{th, liquid}} \) | W/(m K)   | 105    |
| Density (solid) \( \rho_{\text{solid}} \) | kg/m³     | 2700   |
| Density (liquid) \( \rho_{\text{liquid}} \) | kg/m³     | 2220   |
| Kinematic viscosity \( \nu \) | m²/s       | 4.08⋅10⁻⁷ |
| Mushy zone constant \( C \) | kg/(m³ s)  | 10⁻⁷   |
| Small value (Darcy) \( b \) | -          | 10⁻⁷   |
| Focal / Keyhole diameter \( d_f \) | µm         | 500    |

3. Determination of factors influencing the melt flow

By separate modification of the boundary conditions of the model, the effect of different phenomena on the resulting melt flow can be investigated. In this section, the influence of viscosity in the melt and friction at the keyhole wall is analysed.

3.1. Influence of viscosity in the melt

The influence of the viscosity in the melt was investigated by comparison of the fluid flow with a kinematic viscosity \( \nu \) of zero to the fluid flow with \( \nu = \nu_{\text{aluminium}} = 4.08\cdot10^{-7} \) m²/s.

The flow fields resulting from the simulation with \( \nu = 0 \) m²/s are given in Figure 2a with \( u_{\text{weld}} = 6 \) m/min (top) and \( u_{\text{weld}} = 24 \) m/min (bottom). Figure 2b shows the results for \( \nu = 4.08\cdot10^{-7} \) m²/s. All cases were simulated without friction at the keyhole wall, i.e. a slip boundary condition. The local absolute values of the velocity vector \( u_{\text{magn}} \) are indicated according to the colour-coded scale. The upper and the lower limits of the scale indicate the minimum and maximum of the local velocity of the melt \( u_{\text{magn}} \) for all cases with equal welding speed. The white arrows are drawn along sections of individual streamlines to represent the local directions of the fluid flow. The black line shows the contour for \( f_s = 0.5 \), which represents the weld-pool boundary. In order to facilitate the analysis, only the relevant section of the calculation area is depicted in the image. All cases were calculated on the whole mesh, as given in Figure 1.

For all parameters, after melting, at the front of the weld pool, the melt flow is parallel to the welding direction. As expected the velocities in front of the keyhole are low with a stagnation point at the symmetry line. The local velocity increases towards the side of the keyhole.
In case of $u_{\text{weld}} = 6$ m/min, the calculated length of the weld pool was with viscosity 7.6 mm and without viscosity 7.4 mm. Both agree well with the average length of the weld pool $l_{wp} = 8.2 \text{ mm}^{1.0} \pm 1.2 \text{ mm}^{0.5}$ which was measured in the videos presented in previous work [39].

![Fluid flow field a) without viscosity in the melt ($\nu = 0$ m$^2$/s). b) with viscosity in the melt ($\nu = 4.08 \times 10^{-7}$ m$^2$/s). Top: $u_{\text{weld}} = 6$ m/min. Bottom: $u_{\text{weld}} = 24$ m/min. Both cases were calculated with a slip boundary condition at the keyhole wall.](image)

Figure 2. Fluid flow field a) without viscosity in the melt ($\nu = 0$ m$^2$/s). b) with viscosity in the melt ($\nu = 4.08 \times 10^{-7}$ m$^2$/s). Top: $u_{\text{weld}} = 6$ m/min. Bottom: $u_{\text{weld}} = 24$ m/min. Both cases were calculated with a slip boundary condition at the keyhole wall.

The flow field for $\nu = 0$ m$^2$/s in Figure 2a shows different characteristics for both welding speeds. For $u_{\text{weld}} = 6$ m/min a counter-clockwise rotating eddy occurs behind the keyhole with fluid flow opposite to the welding direction and high velocities at the centre line and fluid flow in direction of the weld with high velocities at half of the weld-pool width. The diameter of the eddy is approximately twice the diameter of the keyhole. Behind the eddy, the flow re-attaches to the centreline and continues parallel towards the rear end of the weld pool. Next to the re-attached flow, towards the side of the weld
pool, a wake region occurs with low velocities, as indicated by the blue area. The highest local velocities are about three times as high as the welding speed and occur at the side of the keyhole and in the region of the eddy. When the welding speed is increased to \( u_{\text{weld}} = 24 \text{ m/min} \), only a small instability forms after the keyhole. The flow re-attaches to the centreline directly behind this instability. The wake region at the side of the melt pool is more pronounced, compared to the case with \( u_{\text{weld}} = 6 \text{ m/min} \) with velocities of 0 m/min. The highest local velocities are reached at the side of the keyhole and at the centreline and are approximately five times as high as the welding speed.

As shown in Figure 2b, when viscosity within the melt is considered, at both welding speeds the melt flows around the keyhole and re-attaches to the centreline directly behind it. In both cases this leads to the formation of a wake region towards the side of the melt pool, as indicated by the blue areas. Similarly to the case without viscosity, this wake region is more pronounced for \( u_{\text{weld}} = 24 \text{ m/min} \). Except for the absence of the small eddies behind the keyhole for \( \nu = 4.08 \times 10^{-7} \text{ m}^2 \text{/s} \), similar characteristics of the flow fields occur with and without viscosity in the melt. As expected, the maximum local velocities are lower when the viscosity within the melt is considered.

The results indicate that the consideration of the viscosity in the melt leads to a significant change of the characteristics of the fluid flow only in the region behind the keyhole in case of laser beam welding of aluminium. For both cases, a more distinct separation of the areas behind the keyhole is apparent at higher welding speeds with a small region of high local velocities at the centreline and a wide region of low local velocities towards the side. The absorbed power is similar with and without viscosity and increases from \( P_{\text{depth}} \approx 440 \text{ W/mm} \) at \( u_{\text{weld}} = 6 \text{ m/min} \) to \( P_{\text{depth}} \approx 1030 \text{ W/mm} \) for \( u_{\text{weld}} = 24 \text{ m/min} \). The results show no significant influence of the viscosity in the melt on the resulting weld-pool geometry.

3.2. Influence of friction at the keyhole walls

In order to investigate the interaction between the wall of the keyhole and the melt flow, two cases with different boundary conditions were simulated. In the first case, a flow with friction on the keyhole wall was simulated. This was implemented by a \textit{no slip} boundary condition, where the fluid has zero velocity relative to the keyhole. In the second case, a frictionless flow around the keyhole was modelled. This was implemented by a \textit{slip} boundary condition which sets the radial component of the flow velocity \( u_{\text{rad}} \) at the wall of the keyhole to zero and keeps the tangential component \( u_{\text{tan}} \) unchanged.

The flow field resulting from the simulation with friction at the wall of the keyhole (\textit{no slip}) is depicted in Figure 3a with \( u_{\text{weld}} = 6 \text{ m/min} \) (top) and \( u_{\text{weld}} = 24 \text{ m/min} \) (bottom). In order to facilitate the comparison of these two cases, the flow field without friction at the keyhole as shown above in Figure 2b is shown again in Figure 3b. Both cases were simulated with \( \nu = 4.08 \times 10^{-7} \text{ m}^2 \text{/s} \).

For both welding speeds, the flow with friction at the keyhole, as shown in Figure 3a, has low velocities where the solid material melts and where a stagnation point in front of the keyhole forms. This is similar to the results shown in Figure 2. Behind the keyhole the flow field differs significantly from the case without friction at the keyhole. Towards the side of the keyhole, the flow detaches and high local velocities are reached.

For \( u_{\text{weld}} = 6 \text{ m/min} \), the flow continues parallel to the centre line, as can be seen by the red area. This leads to the formation of a long eddy behind the keyhole. The width of the eddy is approximately equal to the keyhole’s diameter. The local velocities in this eddy are low, as indicated by the dark blue area behind the keyhole. In contrast to the flow without friction at the keyhole, the flow does not attach to the centreline, which leads to higher local velocities in the region at the side of the melt pool.

For \( u_{\text{weld}} = 24 \text{ m/min} \), the flow re-attaches to the centreline. This leads to the formation of two eddies. The first is a counter clockwise rotating eddy behind the keyhole with smaller diameter, compared to the case with the lower welding speed. In the centre of the eddy, low local velocities down to 0 m/min occur. Towards the side of the eddy, these velocities are significantly increased. The second small eddy rotates clockwise and occurs towards the side of the melt pool, where the main flow is re-attached to the centreline. Inside of the wake, an area with zero velocity is formed.
The results indicate that friction at the keyhole walls pronounces the detachment of the flow at the side of the keyhole. This leads to significant changes in the flow field. The characteristics of the flow field change significantly when the welding speed is changed. The maximum local velocity as well as the geometry of the weld pool are not significantly affected by friction at the keyhole wall.

**Figure 3.** Fluid flow field. a) with friction at the keyhole wall (*no slip*) b) without friction at the keyhole wall (*slip*). Top: $u_{\text{weld}} = 6$ m/min. Bottom: $u_{\text{weld}} = 24$ m/min. Both cases were calculated with friction in the fluid ($\nu = 4.08 \times 10^{-7}$ m$^2$/s).

4. **Conclusion**

The proposed reduced numerical model allows for an analysis of the fluid flow during laser beam welding. Different aspects like viscosity in the melt and at the wall of the keyhole can be considered by changing the boundary conditions. This enables the separate analysis of the particular effects.
It was found that the consideration of viscosity in the melt leads to the formation of small eddies behind the keyhole. Besides this no additional effects on the characteristics of the fluid flow were found for laser beam welding of aluminium. A more pronounced effect may occur if materials with higher kinematic viscosity, e.g. steel are considered.

Under the assumption of friction at the wall of the keyhole, a significant influence was found. The flow detaches at the side of the keyhole, which leads to the formation of a counter-clockwise rotating eddy behind the keyhole. For \( u_{\text{weld}} = 6 \, \text{m/min} \) the flow continues parallel to the centre line with high local velocities whereas for \( u_{\text{weld}} = 24 \, \text{m/min} \) the fluid flow re-attaches at the centreline. This leads to higher velocities in the eddy behind the keyhole and at the centreline and subsequently to the formation of a second, clockwise rotating eddy towards the side of the melt pool.

If no friction at the wall of the keyhole is assumed, the overall characteristics of the flow are not changed when the welding speed is increased but the effects are more pronounced: higher local velocities at the centreline and lower velocities towards the side of the melt pool. Furthermore, a more distinct separation of these areas is apparent at higher welding speeds.

Due to the significant difference in the fluid flow the proposed model offers the potential to gain more insight into the interaction between the keyhole wall and the fluid by comparison with experimental results. It is planned to prove experimentally the presence of friction between keyhole and melt.

All results show no significant influence of these boundary conditions on the weld-pool geometry. A reason for this might be that due to the high heat conductivity of aluminium conductive heat transfer is more pronounced compared to convective heat transfer.

Future work will consider laser beam welding of further materials and the implementation of various geometries of vapour capillaries. Due to the short simulation times, the model offers the potential to design optimized keyhole shapes based on needed features in the fluid flow.

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References
[1] Rai R, Elmer J W, Palmer T A and DebRoy T 2007 J. Phys. D: Appl. Phys. 40 5753–66
[2] Berger P, Hügel H, Hess A, Weber R and Graf T 2011 Physics Procedia 12 232–40
[3] Collur M M, Paul A and DebRoy T 1987 Metall and Materi Trans B 18 733–40
[4] Hugger F, Punzel E and Schmidt M 2019 Experimental results and modelling of element loss in continuous laser beam welding of aluminum alloys LiM Lasers in Manufacturing Conference 2019 (Munich, June 24-27) (Munich: WLT Wissenschaftliche Gesellschaft Lasertechnik e.V.)
[5] Mundra K, DebRoy T and Kelkar2 K M 1996 Numerical Heat Transfer, Part A: Applications 29 115–29
[6] Ki H, Mazumder J and Mohanty P S 2002 MTAT 33 1817–30
[7] Vázquez R G, Koch H M and Otto A 2014 Physics Procedia 56 1334–42
[8] Sonti N and Amateau M F 1989 Numerical Heat Transfer, Part A: Applications 16 351–70
[9] Zhao H and DebRoy T 2003 Journal of Applied Physics 93 10089–96
[10] Kaplan A 1994 J. Phys. D: Appl. Phys. 27 1805–14
[11] Schuoecker D and Kaplan A F H 1994 Overview of modeling for laser applications Laser Materials Processing: Industrial and Microelectronics Applications Europto High Power Lasers and Laser Applications V (Vienna, Austria, Sunday 3 April 1994) (SPIE Proceedings) ed E Beyer et al (SPIE) p 236
[12] Tan W and Shin Y C 2014 J. Phys. D: Appl. Phys. 47 345501
[13] Cho J-H and Na S-J 2006 J. Phys. D: Appl. Phys. 39 5372–8
[14] Otto A and Schmidt M 2010 Physics Procedia 5 35–46
[15] Gao X S, Wu C S, Goecke S F and Kügler H 2017 Journal of Materials Processing Technology 242 147–59
[16] Otto A, Koch H and Vazquez R G 2012 Physics Procedia 39 843–52
[17] Rodgers T M, Madison J D and Tikare V 2017 Computational Materials Science 135 78–89
[18] Han R, Li Y and Lu S 2017 International Journal of Heat and Mass Transfer 106 1345–55
[19] Wei H L, Elmer J W and DebRoy T 2017 Acta Materialia 126 413–25
[20] Wei H L, Elmer J W and DebRoy T 2017 Acta Materialia 133 10–20
[21] Draxler J, Edberg J, Andersson J and Lindgren L-E 2019 Weld World 63 1489–502
[22] Bakir N, Üstündağ Ö, Gumenyuk A and Rethmeier M 2020 Weld World 64 501–11
[23] Wei Y H, Dong Z B, Liu R P and Dong Z J 2005 EWeld J (NY) 13 437–54
[24] Prieto C, Vaamonde E, Diego-Vallejo D, Jimenez J, Urbach B, Vdne Y and Shekel E 2020 Procedia CIRP 94 596–600
[25] Jarwitz M, Lind J, Weber R, Graf T, Speker N and Haug P 2018 International Congress on Applications of Lasers & Electro-Optics 2018 703
[26] Wang L, Mohammadpour M, Yang B, Gao X, Lavoie J-P, Kleine K, Kong F and Kovacevic R 2020 Applied optics 59 1576–84
[27] Jasak H and Weller H G 2000 Int. J. Numer. Meth. Engng 48 267–87
[28] Weller H G, Tabor G, Jasak H and Fureby C 1998 Int. J. Numer. Meth. Engng 12 620
[29] Blomberg T 1996 Heat conduction in two and three dimensions: Computer modelling of building physics applications (Report / TVBH vol 1008) (Lund)
[30] Rösler F and Brüggemann D 2011 Heat Mass Transfer 47 1027–33
[31] Fetzer F, Stritt P, Berger P, Weber R and Graf T 2017 Journal of Laser Applications 29 22012
[32] Issa R 1986 International Journal of Computational Physics 62 40–65
[33] Moukalled F, Mangani L and M D 2016 The finite volume method in computational fluid dynamics: An advanced introduction with OpenFOAM and Matlab (Cham, Switzerland: Springer)
[34] Ferziger J H, Perić M and Street R L 2020 Computational Methods for Fluid Dynamics (Cham: Springer International Publishing)
[35] Voller V R and Prakash C 1987 International Journal of Heat and Mass Transfer 30 1709–19
[36] Fetzer F, Hagenlocher C, Weber R and Graf T 2021 Optics & Laser Technology 133 106562
[37] Kammer C 1998 Aluminium-Taschenbuch 15th edn (Düsseldorf: Aluminium-Verlag)
[38] Leitner M, Leitner T, Schmon A, Aziz K and Pottlacher G 2017 MTA 48 3036–45
[39] Hagenlocher C, Weller D, Weber R and Graf T 2019 Science and Technology of Welding and Joining 24 313–9