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COUPLING FEM AND CFD SOLVERS FOR CONTINUOUS CASTING PROCESS SIMULATION USING PRECICE

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Abstract. The numerical investigation of continuous casting requires more than just one simulation technique. In continuous casting, liquid metal is continuously poured into a mould while the starting head is slowly moved downwards, which results in a growing metal ingot. Though, the ingot's outer surface is solidified after the mould, its inside core is still a mixture of liquid and mushy phases. This mixture of physical states requires different numerical schemes to describe the constitutive behaviour and relation. While the liquid region is described in the Eulerian approach, the solid is well described in the Lagrangian approach. Commonly the finite volume method is chosen for the Eulerian and the finite element method for the Lagrangian perspective. Consequently, it is logical to combine a CFD solver with a FEM solver for an ideal numerical representation of the continuous casting process. The coupling of two different solvers communicating in two different programming languages - in the present work OpenFOAM and LS-DYNA - is not an easy task. However, preCICE enables the coupling of the different solvers with a minimum of intrusive functions.

The present work deals with the first step towards the coupled simulation routine for the continuous casting process. A first basic simulation of a simple plate was setup consisting of OpenFOAM for the Eulerian approach and LS-DYNA for the Lagrangian approach. OpenFOAM calculates the temperature field due to time-dependent boundary conditions, while the mechanical LS-DYNA solver calculates resulting strains and stresses considering thermal strain. The aim of this simulation was to develop and test the preCICE adapter for LS-DYNA, as the adapter for OpenFOAM is already available and ready to use. The mapping techniques of preCICE did manage to achieve good energy conservation results. The first results showed a good correlation especially in the middle of the domain. The difference at the plates' ends between the two different methods defined the next steps for the coupling.

1 INTRODUCTION

As pointed out in [1] the attitude of modern society is changing. Sustainability and energy efficiency became more important throughout the different industries. These changes also had a big impact on metal casting. Although metal casting processes are well established over a long period of time, the casting industry is facing new challenges according to the change in society as described in [2], leading to the need for continuous process improvement and its prominent role in today's industries.

The improvement of well established processes is in general more difficult. They demand for an in-depth knowledge about the process and the full understanding of its phenomena. In [3] the importance of numerical models is described. They are generally capable of simulating the details of the phenomena and mechanisms involved in the processes. The continuous casting process is no exception. Its virtual representation can help to solve the arisen challenges.

The continuous casting process is a very complex process, especially from the viewpoint of a numerical simulation. According to [4], the numerical model has to consider thermal, mechanical, electromagnetic, hydrodynamic and free boundary phenomena. All of these phenomena are strongly dependent on the chosen material and its properties. Besides the influence of the phenomena, the material properties greatly influence the casting process and its parameters. Especially the casting of high strength aluminium alloys is critical due to the limited ductility and the resulting risk of hot tearing or cold cracking as outlined in [5].

1.1 State of the art

The requirements, constraints and boundary conditions of a simulation model specify the ideal numerical method. Each method has its strength and weaknesses. Especially for a process involving a lot of different phenomena it is normal that a variety of solution methods exist, as different physical aspects are addressed and challenged.

In [6] the role of coupling different length scales as well as the interaction between the fluid flow and solidification phenomena is addressed. Furthermore, it is outlined that a strong and complex coupling between the physical phenomena at different scales is crucial for a correct description of the process by means of numerical simulations.

In [7] the need for the simulation of flow related phenomena and the simulation of stress and deformation is described. A simulation method is proposed to simulate the solidification while considering elastic stresses implemented in the Finite Volume Method (FVM) based solver OpenFOAM.

In [5], a simulation model for the continuous casting process has been developed based on the Finite Element Method (FEM) solver ALSIM5. The goal of this approach was to receive in-depth understanding of the thermo-mechanical thermo-mechanical processes in the ingot during the casting process. Hereby, the time-dependent boundary conditions have been defined to consider thermal field effects. The heat flow due to convective heat

transfer is apparently not solved within ALSIM5. A criterion for cold cracking has been proposed to predict failure mechanisms in the process and to improve the production efficiency of high strength aluminium alloys.
Another approach is documented in [4], where the continuous casting process is simulated in a simplified manner with a sole FEM solver, where convective heat transfer and resulting heat flow are neglected.

1.2 Motivation

Continuous casting involves many different physical phenomena. These phenomena will mostly inquire different solver formulations as well as different software products. In addition, it is often desired to use already in-house available software products. Hence, the coupling of the different physical domains and involved solvers is of great interest to develop a reliable and agile simulation model.
This paper presents a solution for the coupling of a FVM based CFD solver and a FEM based structural solver by means of preCICE [8]. The FVM based CFD solver is ideal for the simulation of the fluid flow and the resulting temperature field considering convective and conductive heat transfer. The FEM based structural solver is capable of simulating deformations of structures, hence resulting strain and stress fields.
In section two a first pilot study will be presented together with the phyiscal and numerical setup. Afterwards, in section 3 the results of the first pilot study are shown before those are being discussed in section 4. The final outlook will deal with the next steps for the setup of a continuous casting process simulation based on a coupled FVM based CFD solver and a FEM based structural solver.

2 SETUP

A strongly simplified setup is defined aligned with the requirements of a continuous casting simulation. It serves as a first pilot study for coupling the commercial FE Code LS-DYNA (R9.3.0) with a CFD solver via the coupling library preCICE (v1.3.0). Since, the main objective of this work is the development and implementation of a preCICE adapter in LS-DYNA, it was necessary to test the adapter for its functionality. To do so, the second participant should have an established and tested adapter. OpenFOAM (v5.0) is chosen as CFD solver and second participant in the coupling, as this adapter is already available [9]. More specifically, OpenFOAM's *laplacianFoam* is chosen for solving the heat equation. In the current version of the OpenFOAM adapter, the exchange of the temperature fields is restricted to patches. Patches are restricted to surfaces and so they are excluding data mapping within volume elements [9]. Therefore, the geometrical setup is defined such, that it can be meshed with a single volume or element in the thickness direction. In this way, the definition of patches provides comparable data as the volumetric definition would provide for the chosen test setup. Furthermore, the deformations will be kept small since displacements are not mapped from LS-DYNA to OpenFOAM in this investigation. Nevertheless, the elastic behaviour of the material should be observable, resulting in elastic stresses.

For ease of complexity, the geometry is defined as a rectangular, thin walled plate with the dimensions L_x, L_y and L_z (see figure 1). The plate is fixed against motion in x-direction on both ends. In addition, the two points A and B are fully constrained to prevent rigid body motion. A transient, structural mechanical analysis is applied to the plate considering thermal expansion with the material density ρ, Young's modulus E, Poisson's ratio ν and the linear thermal expansion coefficient α_T. The thermal diffusivity α is determined by $\alpha = \lambda/(\rho c_p)$ with the thermal conductivity λ and the specific heat capacity c_p (see table 1).

Table 1: Material parameters and boundary conditions for the simulation setup

Parameter	symbol	value	units
density	ρ	2700	kg/m^3
Young's modulus	E	71000	N/mm^2
Poissons's ratio	ν	0.3	–
thermal expansion coefficient	α_T	$22.5 \cdot 10^{-6}$	$1/K$
thermal diffusivity	α	$9.7 \cdot 10^{-5}$	m^2/s
thermal conductivity	λ	237	$W/(mK)$
specific heat capacity	c_p	910	$J/(kgK)$
initial temperature	T_{init}	293	K
temperature increase	ΔT	6.67	K/s
total simulation time	t_{tot}	30	s
fixed time step	Δt	1.0	s

The plate is initialised with the temperature T_{init}. An adiabatic Neumann condition is applied for the heat equation as ($\frac{d}{dx}T(x = 0, t) = 0$) on the left wall at $x = 0$. At $x = L_x$ the wall temperature increases over time. This time dependent boundary condition describes as $T(x = L_x, t) = T_{init} + t/t_{tot} \cdot \Delta T$ with the temperature increase ΔT over the total simulation time t_{tot} (see table 1).

The domain is discretised with different meshes (see table 2). *Mesh 1* is denoted as the reference mesh. Thisis also applied for a standalone thermomechanical LS-DYNA simulation. The variation of meshes in the OpenFOAM simulations results in non-conforming meshes with respect to the reference mesh used by LS-DYNA. In LS-DYNA the element formulation *elform 1* is applied. The OpenFOAM discretisation schemes are the default for the laplacianFoam solver.

The total simulation time t_{tot} is discretised using a fixed time step Δt with an implicit Euler time stepping scheme for both solvers. The fixed time step was chosen to simplify the programming of the preCICE adapter for LS-DYNA. Although the time step management would theoretically be possible with preCICE, it demands for more access and

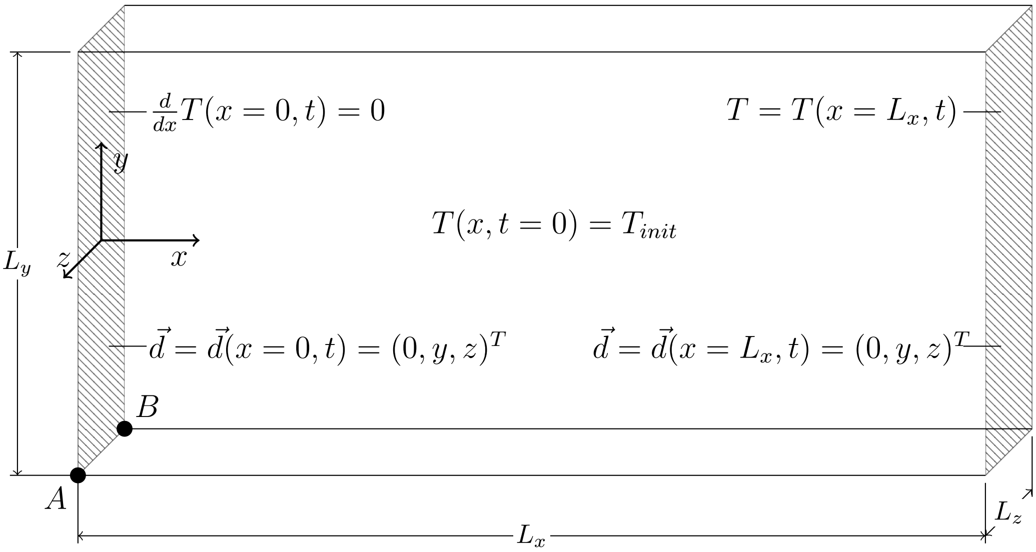


Figure 1: Numerical setup with thermal and mechanical boundary conditions: the temperature T is initialised with T_{init} on the whole domain and constrained at $x = 0$ and $x = L_x$; the displacements $\vec{d}$ are restricted at $x = 0$ and $x = L_x$ in x-direction whereas the displacements at the points A and B are fully restricted as $\vec{d} = (0, 0, 0)^T$

intrusive interfacing which is not guaranteed to work. Therefore, an adaptive time step was excluded in the first phase of adapter development.
The preCICE configuration file defines the main parameters for the coupling. In this present case, the calculation of the mapping matrix is done at the very beginning of the simulation. The data is transferred in a two-way coupling from OpenFOAM to LS-DYNA and vice versa in a consistent way. Though, the data transferred from LS-DYNA to OpenFOAM are currently only dummy data with $T_{(Sink)} = 0$.
While in LS-DYNA the temperature data is stored on the nodes (corners of an element), the data storage in OpenFOAM depends on the coupling settings. In this case, data is stored on the *faceCentres*, as option *faceNodes* did not work correctly with the used OpenFOAM adapter. Followingly, the vertices for data transfer do never conform. As a consequence, the choice for the mapping algorithm and its settings was quite impor-

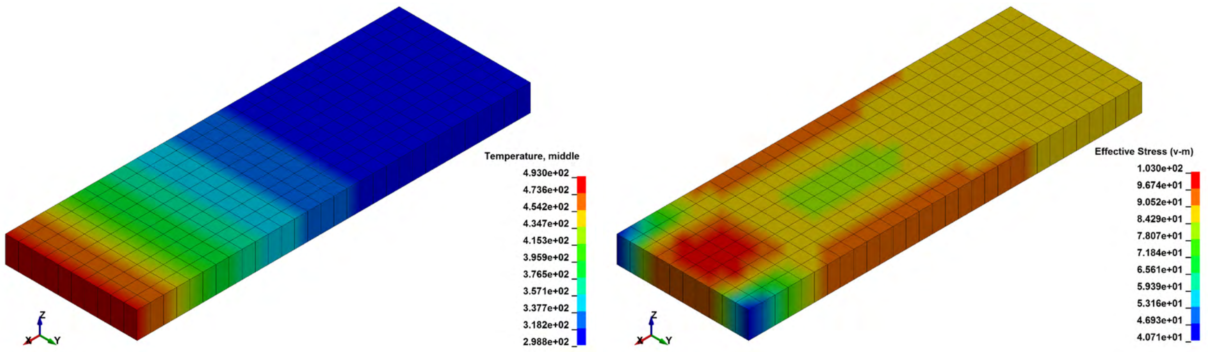
Table 2: Overview of the different, used mesh parameters

Simulation	elem. type	discr. in x	discr. in y	discr. in z	tot. elements
LS-DYNA mesh	hex	30	10	1	300
OpenFOAM mesh 1	hex	30	10	1	300
OpenFOAM mesh 2	hex	75	25	1	1875
OpenFOAM mesh 3	tet	30	10	1	3275
OpenFOAM mesh 4	tet	75	25	1	37591

tant. preCICE has to extrapolate data from the OpenFoam points to the LS-DYNA nodes. Thin plate splines are applied for spatial mapping, as they have provided the best mappping results. A thermo-mechanical simulation was set up for the development of the preCICE adapter for LS-DYNA to compare and validate the results of the coupled solvers. In the following, this themo-mechanical simulation is referred to as the reference solution.

3 RESULTS

Figure 2 shows the final contour plots for the temperature (3a) and the von Mises (2b) equivalent stress of the thermo-mechanical reference simulation in LS-DYNA. The contour plot of the temperature shows the temperature field increasing from 299 K to 493 K. The absence of externally applied forces means that the von Mises equivalent stress ranging from 40 MPa to 103 MPa are induced by the thermal strains. So, It is necessary to validate the temperature field between the original OpenFOAM values and the received LS-DYNA values versus the thermo-mechanical solution within LS-DYNA.



(a) Temperature contour plot

(b) Von Mises stress contour plot

Figure 2: Contour plots at $t = t_{tot}$ for the thermo-mechanical calculation with LS-DYNA

Figure 3 shows the temperature curves for the different simulations and compares the thermo-mechanical LS-DYNA calculation. However, the absolute values are not of great interest only the the difference to the original temperature field. Thereby the temperature has been normalised. Θ corresponds to the normalised temperature difference as $\Theta = (T - T_{init})/\Delta T$. While figure 3a shows the complete temperature curve along the interface, figure 3b and figure 3c are detailed to $0 \leqslant x \leqslant 0.1$ andto $0.95 \leqslant x \leqslant 1.0$, respectively. The overall view shows a good correlation between the reference curve and the results of the coupled simulations. With the detailed views it can be seen, that the temperatures of the coupled simulations are overestimating at $x = 0$ and underestimating at $x = L$.

Table 3 shows the energy conservation during data transfer. Therefore, the total thermal energy in OpenFOAM (E_{OF}) and LS-DYNA (E_{LS}), respectively, was calculated. In addition, the total error between E_{OF} and E_{LS} was calculated with resprect to the total thermal energy in OpenFOAM. The thermal energy E_{OF} shows a slight difference between the hex and tet meshes. The thermal energies between the coarse and fine meshes are very close. The energies E_{LS} are always very close to the original energies E_{OF}, as the total errors show with values between 10^{-4} and 10^{-6}

Table 3: Energy conservation

simulation	E_{OF}	E_{LS}	total error
1	0.0260831	0.0260832	$3.8 \cdot 10^{-6}$
2	0.0260833	0.0260869	$1.4 \cdot 10^{-4}$
3	0.0261217	0.0261191	$-1.0 \cdot 10^{-4}$
4	0.0261257	0.0261224	$1.3 \cdot 10^{-4}$

4 DISCUSSION

The main goal of the presented simulations and results was to develop a first draft of a preCICE adapter for LS-DYNA and show the applicability of preCICE for future process simulations.

The comparison of the normalised temperature curves at $t = t_{end}$ shows a very good agreement with a very small total error between 10^{-4} and 10^{-6}. The detailed view at the beginning and the end of the interface for $x = 0$ and $x = L$ shows deviations of about 3% with the chosen mapping setup. With the OpenFOAM data points at the face centres and the LS-DYNA data points on the nodes (corners of the elements) the temperature values in the LS-DYNA on the left and right boundary area of the geometry are extrapolated.

The general mapping was sufficiently precise, apart from the missing mapping inside of the exemplary geometry. The error for the total energy of the OpenFOAM is negligible compared to the LS-DYNA calculation.

5 OUTLOOK

The described work presents a first step towards a continuous casting process simulation consisting of a FEM based structural solver coupled to a FVM based CFD solver to increase the predictability of the temperature field. In the future, it is necessary to gradually increase the complexity in order to be able to describe the continuous casting process . Hereby, it is planned to introduce fluid flow inside the liquid metal in order to calculate the convection driven temperature field. Afterwards, the phase change from the liquid metal to the solid material has to be implemented.

The available OpenFOAM adapter does not include volume mapping, the simulation setup was choosen as an interface (surface) mapping or a quasi-2D problem, which is no option for future process simulation. In the future, the final setup of the simulation has to be a volume mapping.

These steps can be done based on the presented setup. However, the setup also has to be extended to a two-way coupling, to consider the displacement and its consequences on to the cooling behaviour.

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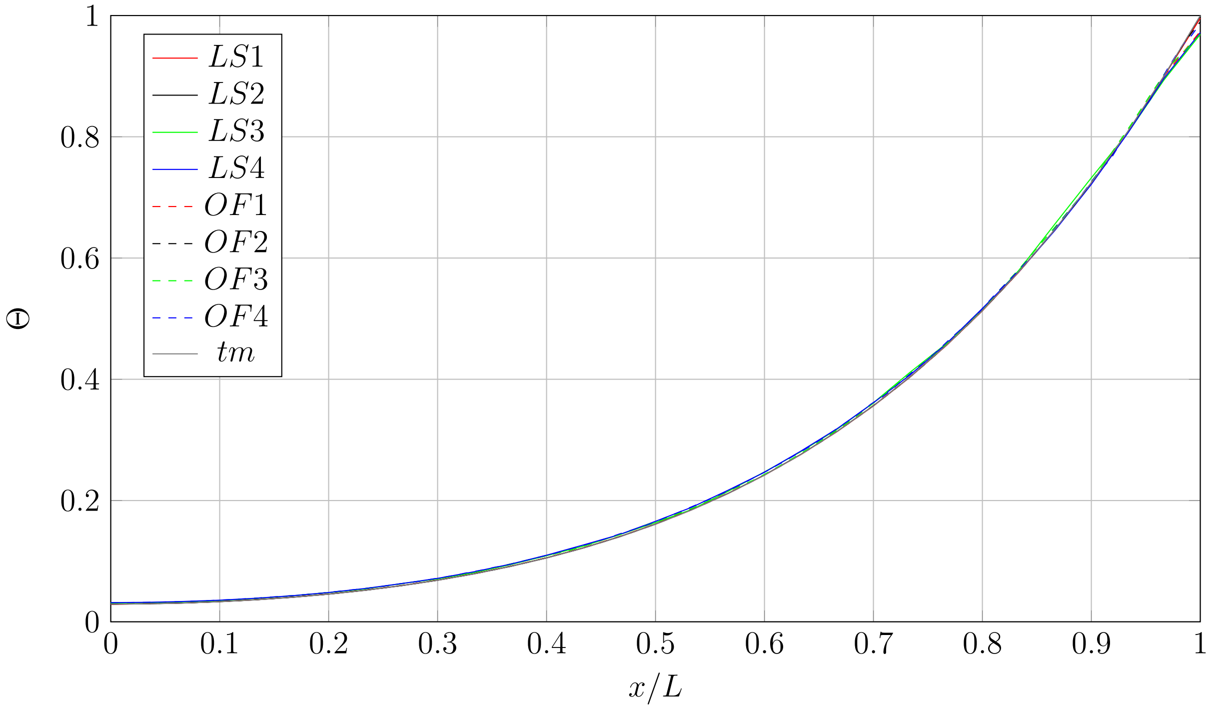
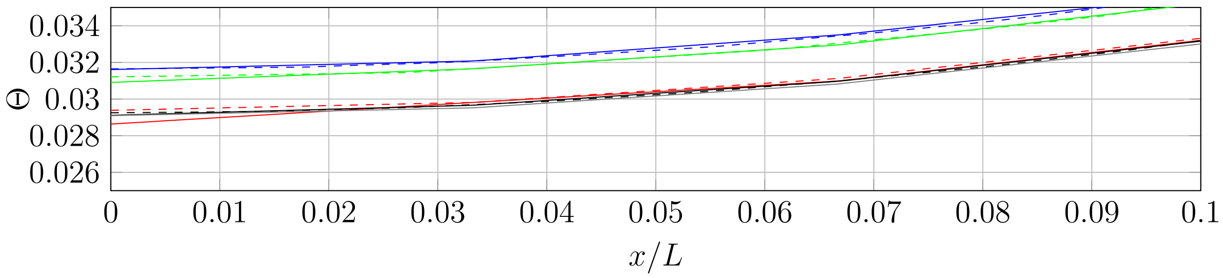
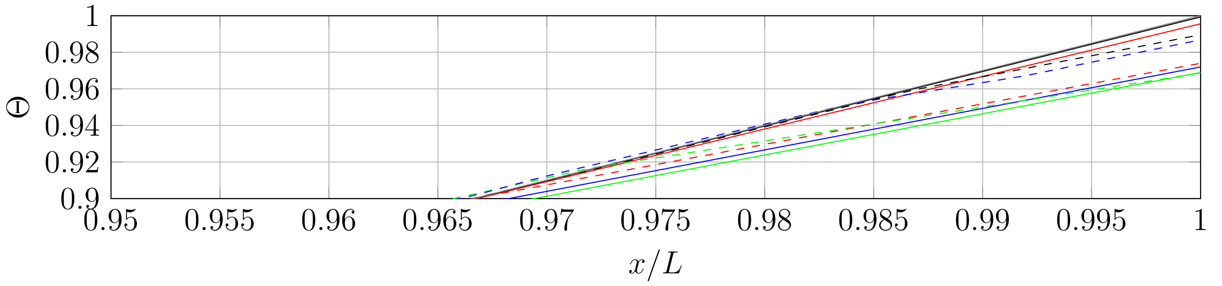


(a) Relative temperature along the interface



(b) Relative temperature for $0 \leqslant x \leqslant 0.1$



(c) Relative temperature for $0.95 \leqslant x \leqslant 1.0$

Figure 3: Temperature for the quasi-2D conduction case with LS corresponding to the results of the mechanical solver LS-DYNA, OF corresponding to the thermal solver OpenFOAM and tm corresponding to the reference solution