STATE OF THE ART IN MODELLING OF CONTINUOUS CASTING

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ABSTRACT

Numerical simulation tools for continuous casting processes have recently been enriched with a new innovative technique based on a Mixed Lagrangian Eulerian Method (further noted as MiLE) implemented in the finite element software ProCAST. In order to treat non-steady phenomena in continuous casting, one has to consider an extending computation domain : as casting proceeds, new elements have to be added to or activated in the existing mesh. In the MiLE approach, this is done by separating the casting into two domains. The first one, which contains the top of the liquid pool, is of fixed size and is treated with an Eulerian algorithm. In the second one, the approach is Lagrangian and the domain is moving at a velocity equal to the casting speed. The size of this downstream domain is increased by means of an accordion-like technique: a number of layers of nodes are stored at the interface between the two domains. As casting proceeds, these layers are gradually activated. Thereby, new elements are added to the mesh in order to account for the increasing size of the ingot. This new algorithm allows the coupled modelling of non-steady thermal and fluid flow, as well as the formation of thermally-induced stresses. Applications of this new method covers continuous and DC casting of billets, slabs, blooms or more complex shapes, including straight continuous casting of steels.

The MiLE method complements the other more classical approach used to simulate the steady state thermal and flow behavior during continuous casting of metals, more specifically curved continuous casting of steel and strip casting. In this case the algorithm is fully Eulerian. A transport velocity is applied to the casting material in order to account for advection of heat and liquid flow. Typical results for this type of simulation are the thermal and fluid flow distribution, the metallurgical length and the thickness of the solid shell. The effect of the casting speed and of nozzle design can also be investigated. The behavior of liquid metal in the distribution bag or tundish can also be predicted by classical simulation methods.

The scope of this paper is to present these novel approaches which can be used to help the continuous casting industry to increase the quality and the productivity of their products.

KEYWORDS

Continuous Casting, Numerical modelling, Lagrangian - Eulerian approach, steady state, coupled thermal flow, thermally induced stress, ProCAST.

INTRODUCTION

Numerical modelling of Continuous Casting has been the scope of many studies and is of great interest to help the casting engineers to adjust their process parameters like cooling conditions or casting speed. One primary interest is the prediction of the thermal behaviour of the continuously cast product (billet, slab, bloom, …) once a permanent regime is reached. In DC Casting of aluminium alloys, the start-up phase is also of major interest, whereas for steels, since the process is indeed continuous, the start up phase is rarely considered. Among the results of a simulation, the metallurgical length, the depth of the mushy zone, the liquid pool and the solid shell thickness are

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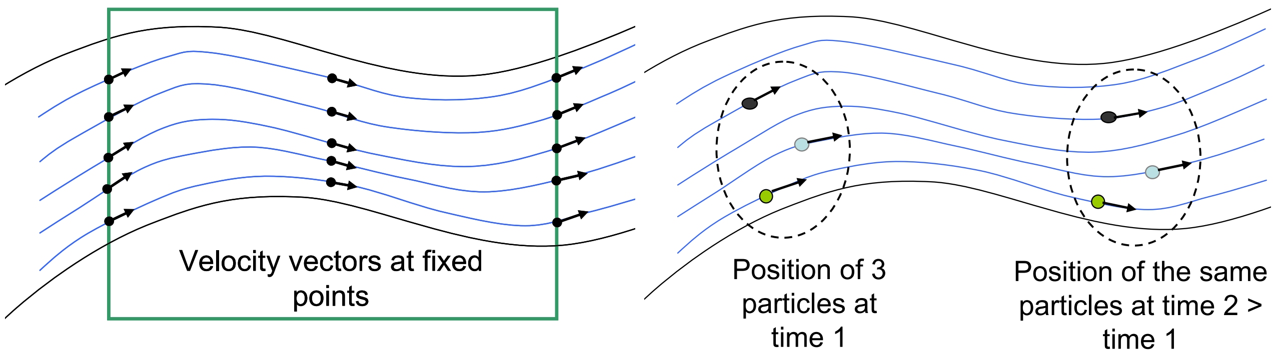
quantities that need to be known. Nowadays, commercial software enables the simulation of the coupled thermal and flow behaviour of the metal when a so called “steady state” is reached. This steady state corresponds to the permanent regime of the process, for a given constant casting speed. For an observer who would be watching the on going metal from a fixed point in the cast house (system of reference), the temperature and velocity vectors at a given fixed points will not evolve with time.

A convenient mathematical approach to model such steady state behaviour is the Eulerian description commonly used in fluid mechanics. With this method, the conservation equations of mass, heat and momentum are written for a fixed open system. It is, so to speak, the point of view of a fisherman watching, from the bank, a river flowing, or of the casting operator watching the continuously cast ingot during the process. This is illustrated by figure 1a, on the left. Conversely, if one follows the fluid particles, like a sailor drifting on his boat or an observer who would be able to follow each particle, the temperature and velocity of the particles will evolve with time, (and of course their positions as well) even at “steady state”. This description is called Lagrangian (see figure 1b, on the right).



a) Eulerian description: the observer is watching a fixed window. At steady state, velocity vectors do not evolve with time.

b) Lagrangian description: the observer has to follow every particle. The velocity vectors of a particle can evolve with time, even at steady state.

Fig. 1: Two different descriptions of a fluid flow (river) at steady state. Velocity vectors are symbolized by arrows, stream lines by blue lines.

Numerical models using the Finite Element Method (FEM) for thermal and flow phenomena in Continuous Casting usually consider a fixed geometry and mesh: the approach is Eulerian. The velocity vectors and temperature fields are computed at fixed node points. However, if one wants to model also the deformation and stress formation of the metal during casting, the Lagrangian description is needed. This type of simulation is of particular interest when one wants to predict the shape (section) of a continuously cast ingot as well as the residual stresses. This allows also the optimization of the tapering of the mould, in order to compensate for the ingot shrinkage. Consequently, if a complete study of Thermal, Flow and Stress behaviour is needed, the problem needs to be addressed with both Lagrangian and Eulerian methods, or with a combination of the two.

The first part of this paper presents the principle of the different numerical models that can be used in the FEM code ProCAST in order to simulate the different aspects of the process. In particular, an innovative Mixed Lagrangian Eulerian approach, called MiLE, is presented. A large part of the paper is then dedicated to applications of these methods to realistic simulations of existing processes.

1. NUMERICAL MODELS

1.1 Steady state approach

The steady state behaviour of temperature and fluid velocity in the metal during continuous casting is usually addressed with an Eulerian approach. With this description, a transport term must be introduced in the conservation equations. In continuous casting, this corresponds to the fact that the casting moves at a velocity given by the casting speed. In the "steady state" modelling approach, this is done by assigning a transport velocity to the computational domain of the metal (or to the solid if fluid flow is activated). In order to reach steady state, a pseudo non-steady calculation is performed (from an initial thermal field defined by the user) until steady state is reached. The temperature history before the steady state is reached has no relevant meaning. The only relevant results are given by the final state, when temperature and velocities do not evolve with time. Note that if the casting is oscillating, like in some continuous casting processes, it is possible to take it into account. One has in this case a pseudo steady state situation.
A major limitation of this method is that it is irrelevant for the computation of strain and stresses in the continuous casting ingot: the deformation and stress state of a volume element is strongly related to its thermal and mechanical history. Moreover, the Lagrangian description is best suited: one has to follow the material point all along the process in order to know its history. Consequently, if one wants to model stress formation (or other transient phenomena like microstructure evolution or porosity) one has to consider a non-steady model.

1.2 Mixed Lagrangian - Eulerian method (MiLE)

Non-steady models of continuous casting can be addressed in several ways. First, one can keep working with a fixed mesh, but in order to model the thermal history, one has to impose some thermal boundary conditions (heat transfer coefficient and external temperature) that will vary with time and space. The principle of this method is presented in figure 2: A fixed geometry is considered (e.g. a curved slab). At time 0, the temperature is that of the incoming the liquid metal.

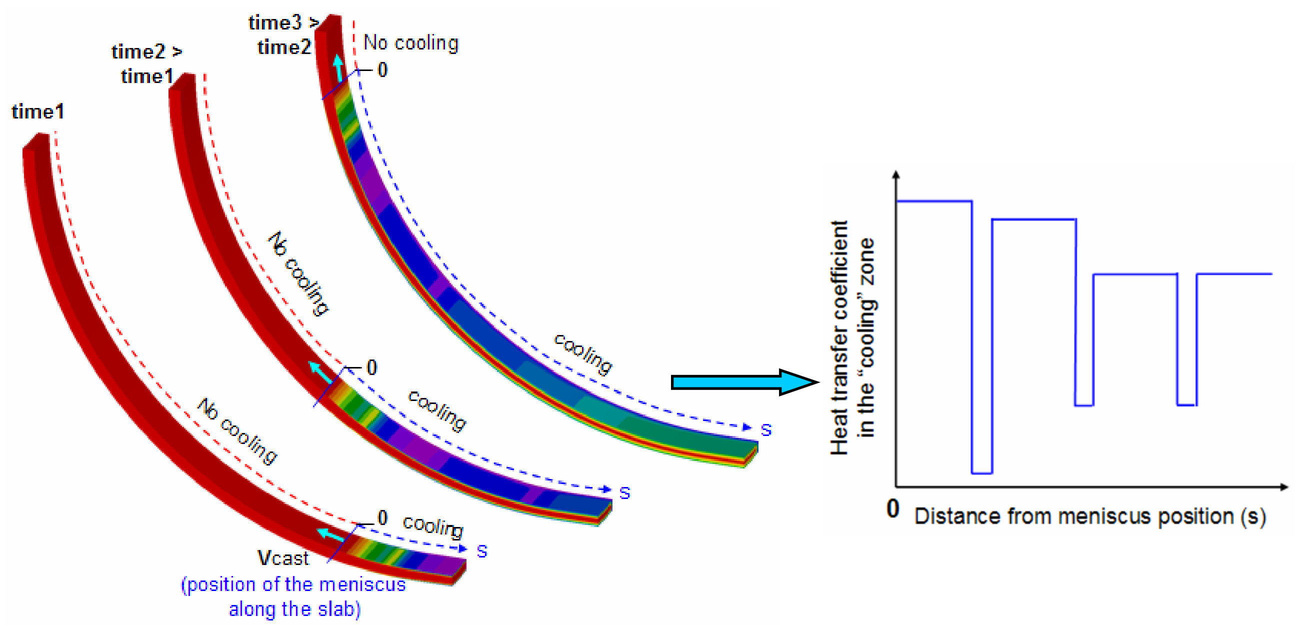


Fig. 2: Schematic principle of the "travelling heat boundary conditions" approach for a curved steel slab. Left: temperature field in the slab at different times. Right: example of a heat transfer coefficient as a function of the distance from the meniscus.

To simulate the thermal history of the slab during casting, a reference line (in blue) is moving up along the slab at a velocity equal to the casting speed. At time t, the distance travelled by this reference line is denoted **s**. By doing so, the slab is separated into two zones: above the line, adiabatic condition is imposed ("no cooling" zone). Below this line, the heat transfer coefficient is a function of the curvilinear distance between the considered node and the position of the reference line **s** which can be viewed as position of the liquid meniscus, in the real casting. For external faces located in the cooling zone, the imposed heat transfer coefficient is a function of the distance from the meniscus. Thus, different cooling can be modelled: primary cooling by mould, water cooling, attenuation due to rolls…

Another possibility is to "build up" the ingot during the simulation by adding successively some layers of elements to the initial mesh. This was done by Drezet and Rappaz [1] in their work on thermo-mechanical behaviour of aluminium alloys DC Casting. This method allowed the modelling of coupled thermal-stress situations, but it was not possible to include fluid flow in the algorithm. In order to allow a full coupling between thermal, flow and stress, a new MiLE algorithm was developed and implemented into ProCAST. This algorithm allows having a computational domain that is enlarging with time, as the continuous casting process goes on. The following figures show the principle of the MiLE algorithm (figure 3), with the region where the calculation is Eulerian and the ones where it is Lagrangian (figure 4).

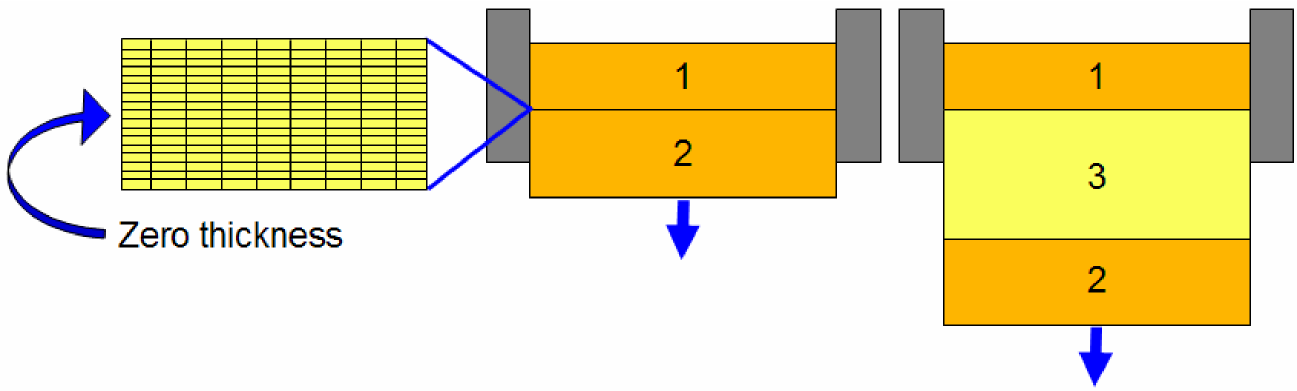


Fig. 3: Schematics of the MiLE algorithm.

At the beginning, the casting is divided into two domains (1 and 2 in the above figure). Then, as the continuous casting process starts, the bottom domain (2) moves down, while the domain 1 stays at its initial position. In order to have continuity between the two domains, new elements have to be introduced (creating the domain 3 above). To make this possible, a number of layers of elements with initial zero thickness is stored at the interface between the two domains. As the downstream domain moves down, the layers are gradually "unfolded", similar to the unfolding of an accordion. By doing so, layers of new elements are introduced on the top of domain 3. To ensure the continuity of temperature and velocities between domains (1) and (3) through the unfolded nodes, some periodic boundary conditions are applied at the interface: all the nodes which have identical coordinates will be given the same field values.

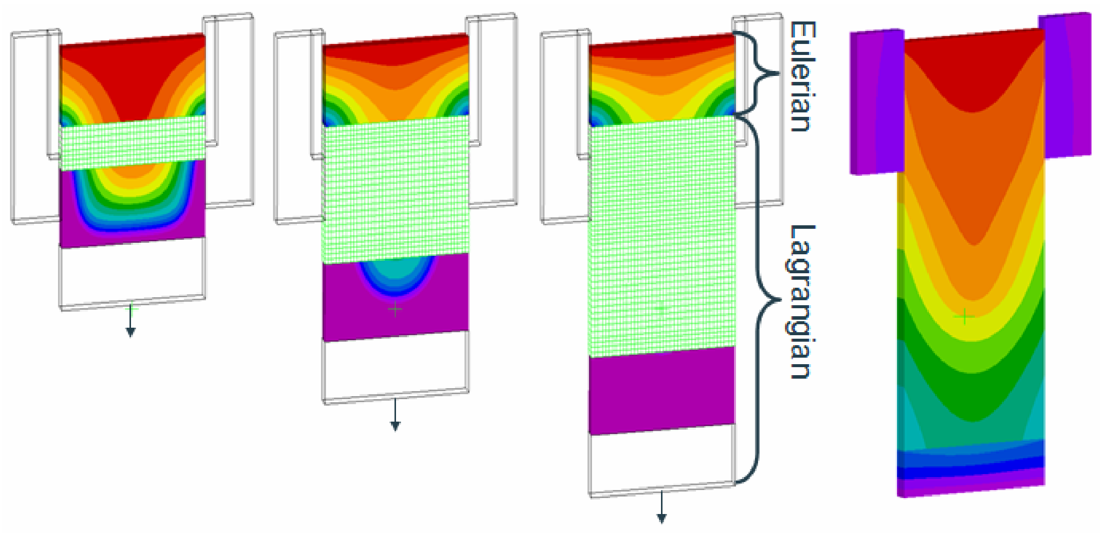


Fig. 4: Principle of the MiLE (Mixed Lagrangian – Eulerian) method.

The third section will illustrate how the different techniques can be applied and combined together in order to model the thermal, fluid flow and stresses behaviour, as well as porosity, in realistic examples.

2. VALIDATION

The MiLE approach was validated through a comparison between results obtained with ProCAST-MiLE and results obtained with ABAQUS, for a thermo-mechanical simulation of an Aluminium DC Casting ingot. The method used in ABAQUS is the one proposed by Drezet and Rappaz and it is described in [1]. The models designed in the two softwares were as close as possible in terms of geometry, mesh, material properties and thermal boundary conditions (cooling of external faces). In order to run these tests, only a quarter of a slab was considered, for symmetry reasons.

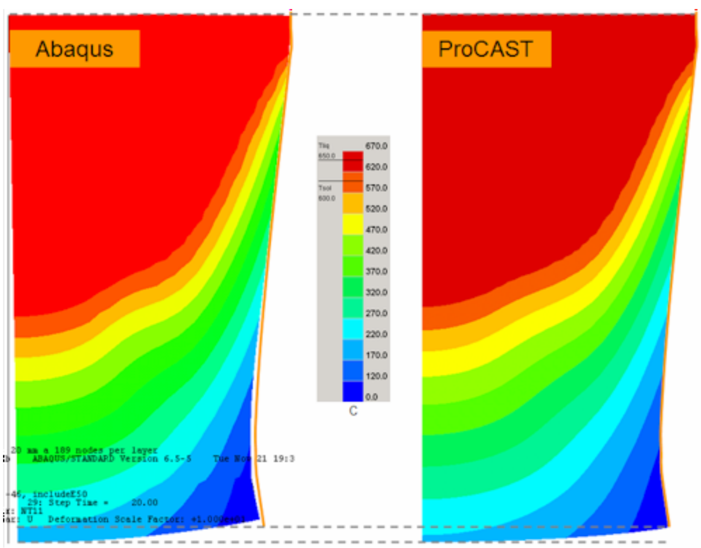


Fig. 5: Comparison between ABAQUS (left) and ProCAST-MiLE (right) for an Al-DC Casting case. Temperature field is shown, together with the shape of the ingot (deformation magnified x10) in the symmetry plane.

The size of the modelled domain is 200 x 500 mm (thus the full slab has a section of 400 mm by 1 meter). The casting speed is 1 mm/s, starting after an initial holding time of 40s. The calculation was run until a total casting height of 1 m.
Figure 5 shows that the comparison of the results in terms of thermal field and deformation of the casting is quite good. It was also verified that the value of stresses (Von Mises and Principal stresses) were very similar in the whole solid part of the casting.

3. EXAMPLES [1]

3.1 Continuous Casting of square steel blooms

As illustrated by figure 6, the comprehensive modelling of a full continuous casting process involves many aspects like: thermal and fluid velocity distributions in the tundish, mould temperature, solidification and cooling of the ingots. This is a very complex situation that can involve a lot of resources in terms of computing time and modelling work. As a consequence, it is more straightforward to study separately each of these aspects. As an example, figure 7 and 8 show what can be done to isolate each problem. First, a study of the coupled thermal and fluid flow behaviour of liquid metal in the tundish can be carried out (figure 7).

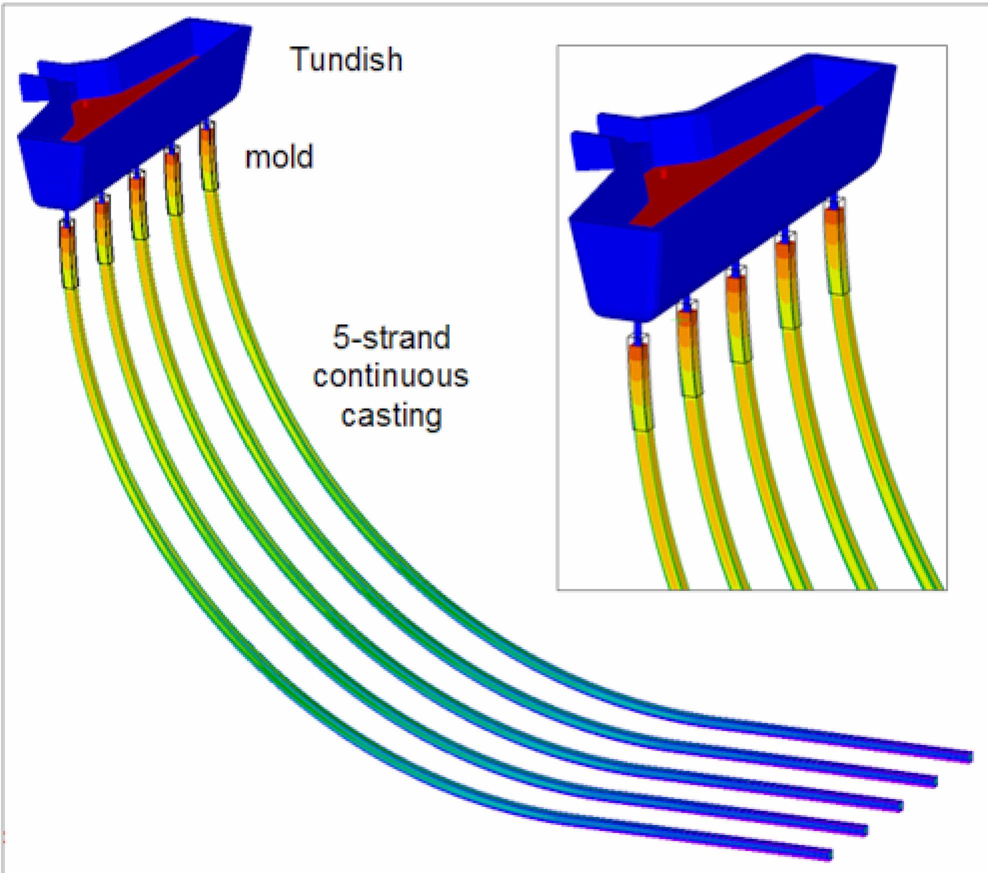


Fig. 6: Comprehensive modelling of a 5-strand continuous casting process. The Temperature field is shown.

[1] Please note that for confidentiality reasons, the exact geometries, process parameters or cooling conditions were changed with respect to the ones of the real processes. As a consequence, some results which are presented in this paper may look different from the reality. However, this does not change the principles of what is illustrated.

Here, the tundish feeds 5 continuous cast strands with liquid metal. As shown by the first picture (7a), the temperature is not homogeneous in the volume and so, the inlet temperature of the metal entering the mould may vary from one bloom to another. The second picture (7b) plots the fluid velocity vectors.

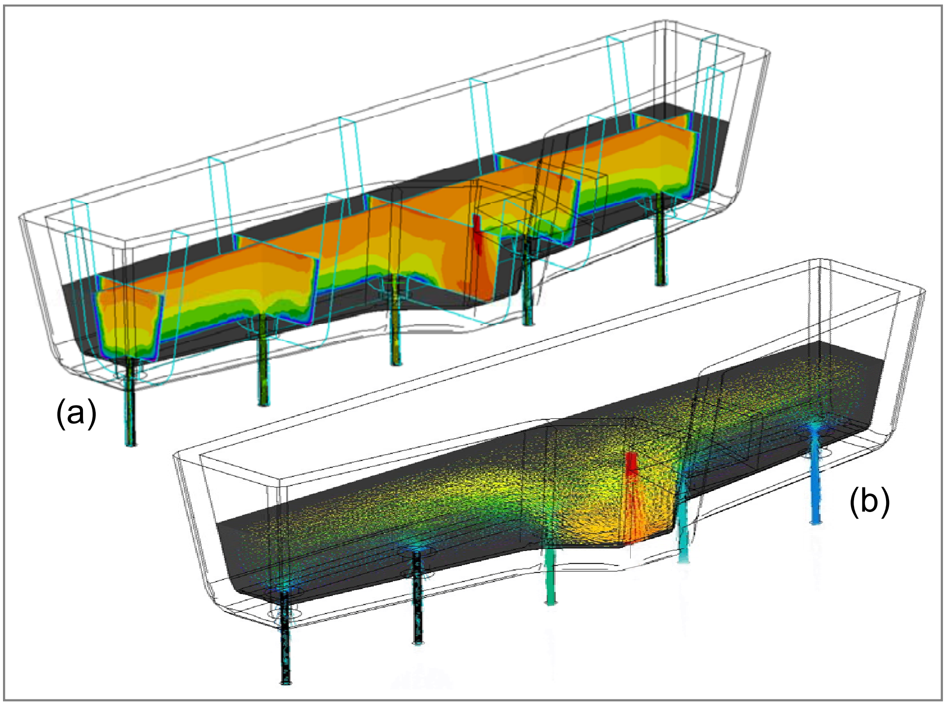


Fig. 7: Behaviour of liquid metal in a tundish. Temperature distribution in several cross-sections (a) and fluid velocity vectors (b). Vectors have their lengths proportional to the velocity magnitude and are coloured with respect to their temperature.

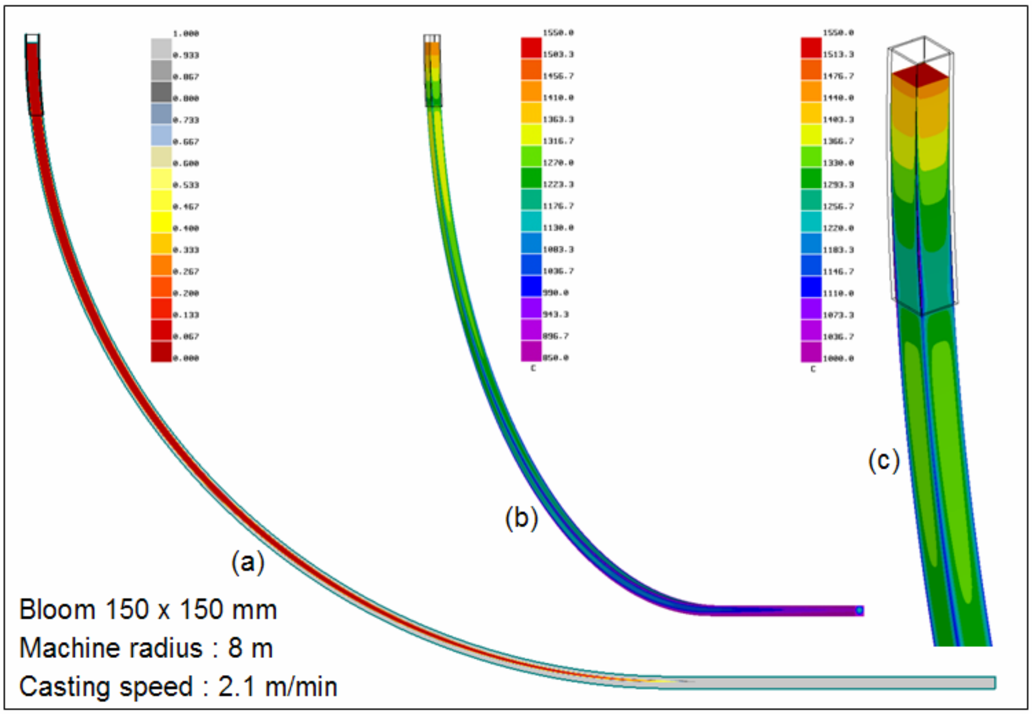


Fig. 8: Solidification of a steel square bloom (steady state). Solid fraction in the middle plane (a), temperature of the external surface (b) and closer look at the mould zone (c).

Then, as shown in figure 8, the solidification of the bloom is investigated. This is done by the "steady state" approach presented in section 1.1. It involves a solid transport velocity, equal to the casting speed, which is tangential to the curved strand. The metallurgical length can be assessed, as well as the thickness of the solid shell. Also, a separate model can be of interest to study the thermal behaviour of metal in the mould zone, with more details (finer mesh, more precise heat boundary conditions or interfacial heat transfer…).

3.2 Continuous casting of "H-shaped" sections

The solidification of more complex shapes of steel continuous casting can also be investigated with the steady state approach. In the same way as the previous example, the temperature field of an "h-shaped" steel casting is computed and shown in figure 9. It is worth noticing that the iso-surface of the solidus and liquidus temperatures are shown in (9c) and (9d). This allows having the depth and shape of the mushy zone and of the liquid pool. These two depths are strongly related to the thickness of the part : the thinner the part, the less deep the liquid pool.

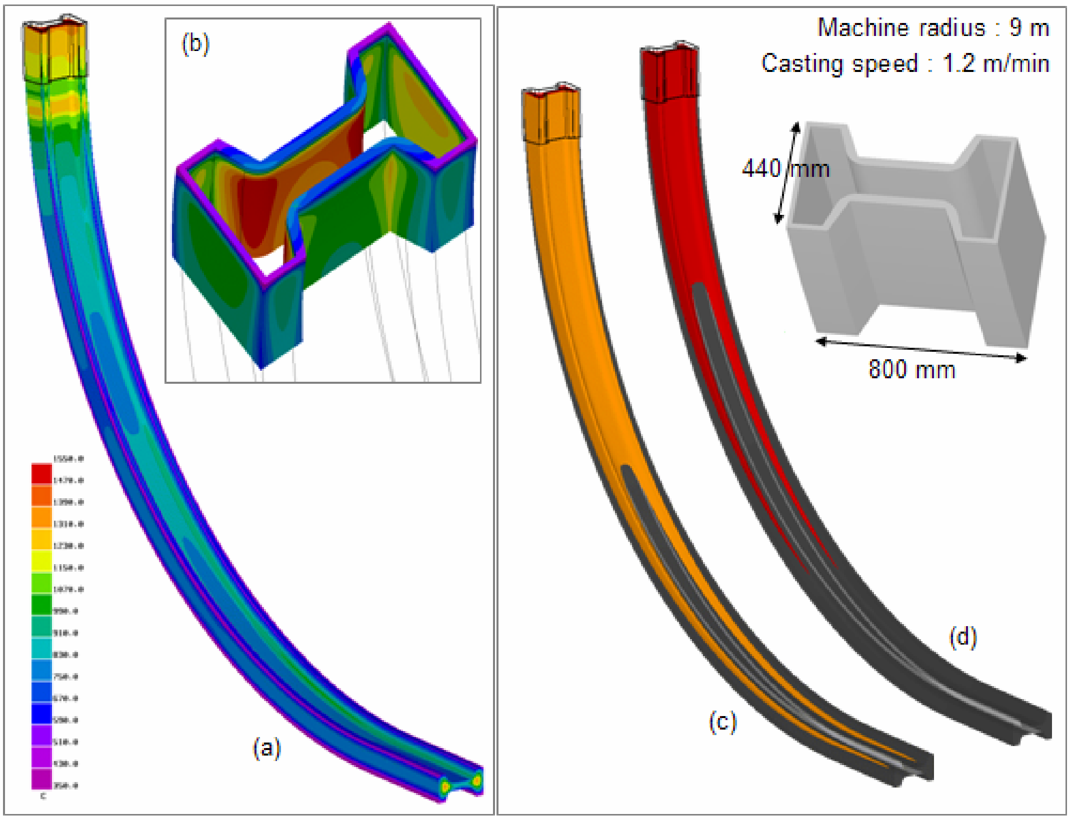


Fig. 9: Solidification of an H shape steel casting (steady state). Temperature of the external surface (a) and in the mould (b) are shown on the left. On the right, cut-off view of the solidus (c) and liquidus (d) iso-surfaces.

3.3 Fluid Flow and thermal behaviour in a nozzle filled mould

In this section, a study of the effect of a nozzle filling on the temperature evolution in the solidifying metal is briefly presented. In figure 10, the effect of the high velocities of incoming hot liquid jets on the solidification and cooling of the metal is demonstrated. In particular, it is clear that the narrow faces are re-heated by the hot incoming liquid (see the part surrounded by a circle on the right).

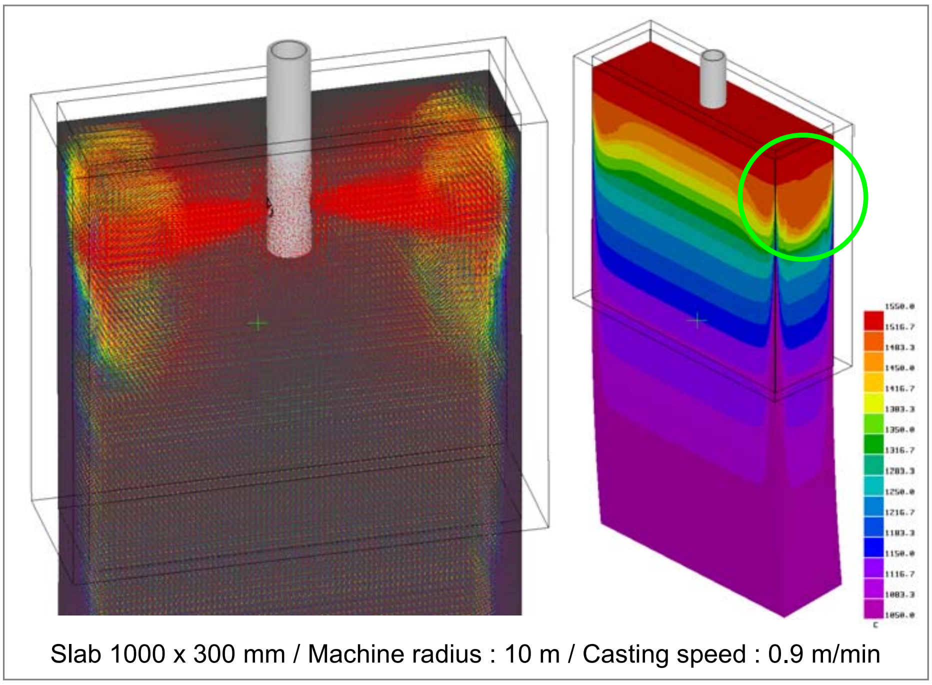


Fig. 10: Coupled thermal-flow behaviour in a mould filled with a cylindrical nozzle. On the left, velocity vectors are coloured with respect to their temperature and have a length proportional to their magnitude.

3.3 Non-steady state study with "travelling" conditions

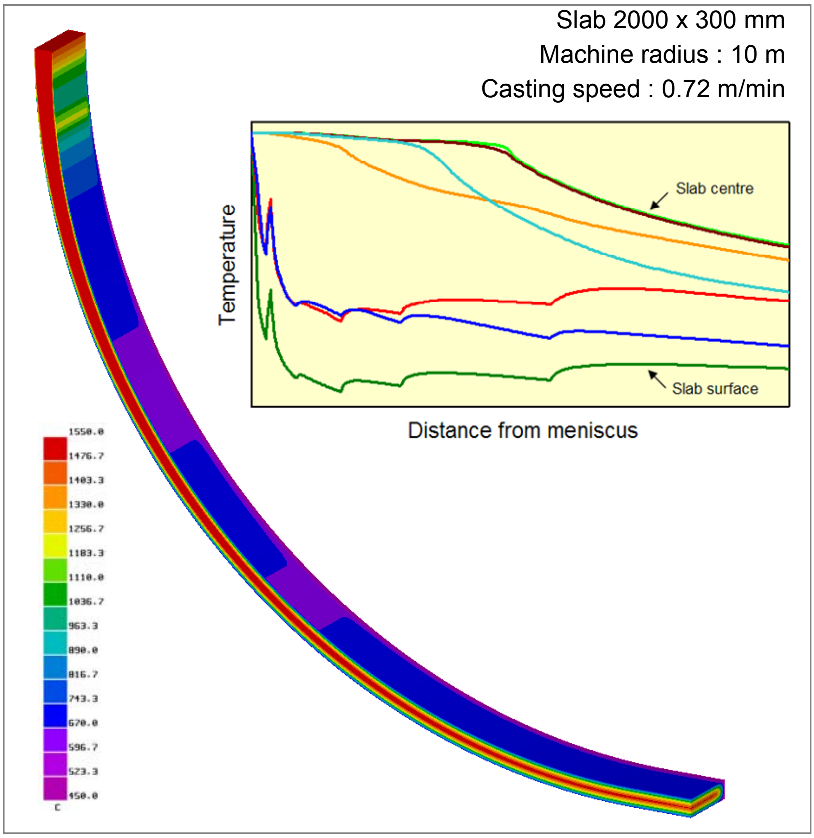


Fig. 11: Non-steady state thermal model of a continuous cast steel slab. Temperature evolution as a function of the distance from the meniscus is shown.

The use of the “travelling boundary conditions” method to produce non-steady state conditions described in section 1 (figure 2) enables the study of the thermal history of the metal during casting. In figure 11, one can see the thermal history – or, equivalently, the temperature evolution as a function of the distance from the liquid meniscus - of some particular nodes taken all through the thickness, from surface to centre. The oscillations of temperature and the re-heatings that can be observed are induced by the imposed cooling conditions that accounts for the different cooling zones : mould cooling, secondary cooling by water jets, attenuation of heat transfer due to rolls, etc.

3.3 MiLE Method for coupled thermal – stress study

As stated in section 1, the MiLE algorithm allows the computation of an expanding domain and is suited for the study of non-steady state phenomena like deformation and stresses induced by thermal contraction and solidification shrinkage. Here, the case of a circular section billet in a tapered mould is presented. The mould tapering consist in an inner conical shape of the mould : the tapering denotes the difference in mould radius between the meniscus and the exit of the mould. Note that for obvious symmetry reasons, only a quarter of the billet has been modelled. Figure 12 shows the temperature evolution in the billet as the casting expands. As casting proceeds, the metal contracts and deforms so that an air gap may form between mould and casting. Also, the stress module of ProCAST allows taking into account the coupled interaction of the billet with the mould, since the heat transfer coefficient is automatically affected by the air gap width.

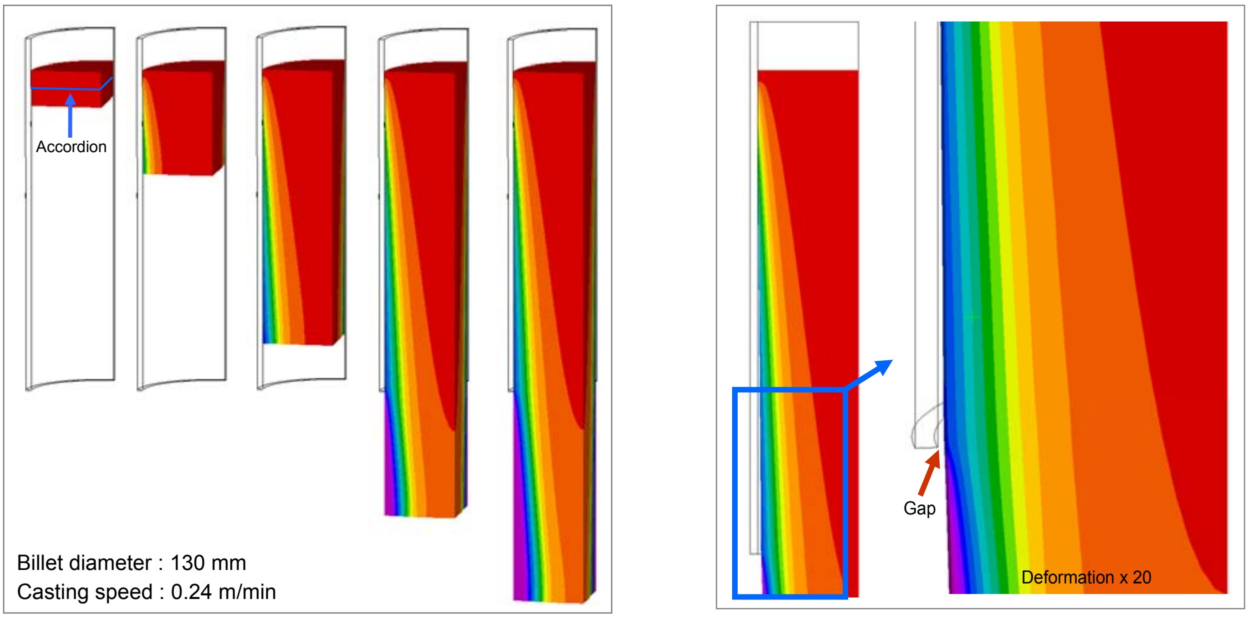


Fig. 12: Coupled Thermal Stress computation of a continuous cast billet with a tapered mould, using the MiLE method. Left: domain evolution with time (thermal field is shown). Right: closer view of gap formation between mould and casting.

In this model, it is of particular interest to see the influence of the mould design on air gap formation, and its consequence on the thermal behaviour (ProCAST allows the full coupling between gap formation due to thermal deformation and the subsequent interfacial heat transfer evolution). Thus, figure 13 shows the gap formation for different mould designs. Three different cases are shown: the computation was done for a cylindrical mould (0 mm tapering) and for two different values of mould tapering (0.1 and 0.2 mm). It can be seen that in the first case, (no tapering), the gap is quite important, whereas for 0.2 mm tapering, there is essentially no more gap : actually the gap that would form due to the deformation of the metal is compensated by the tapering.

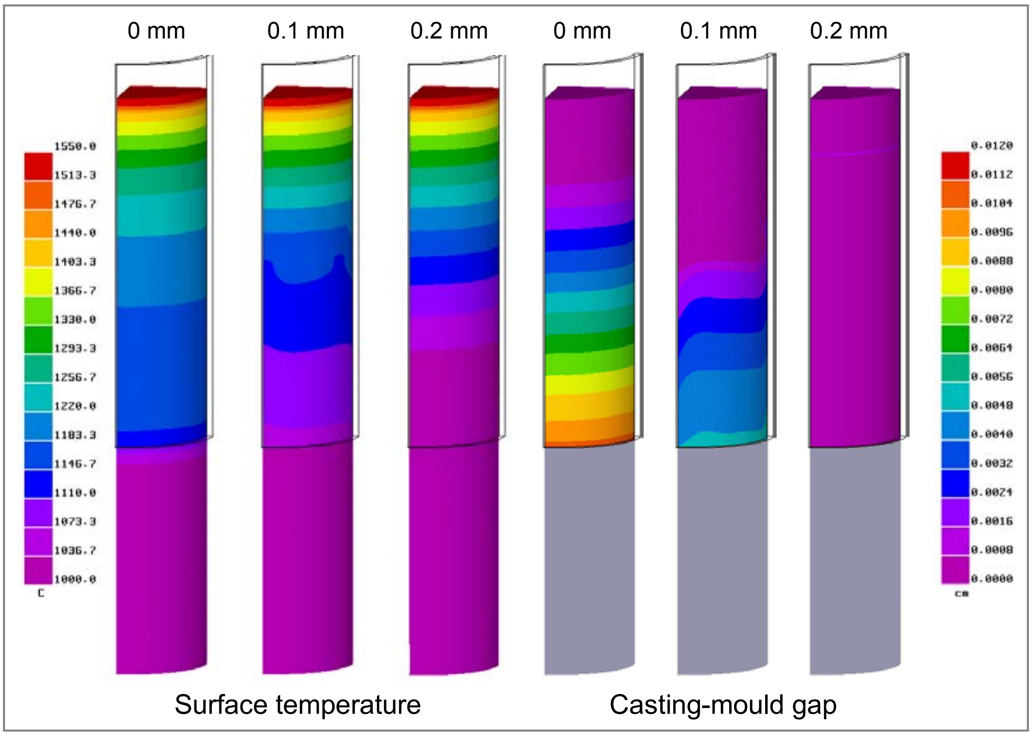


Fig. 13: External surface temperature (left) of the billet and air gap magnitude (right) for different values of “tapering” of the mould : 0 (perfectly cylindrical mould) – 0.1mm and 0.2 mm.

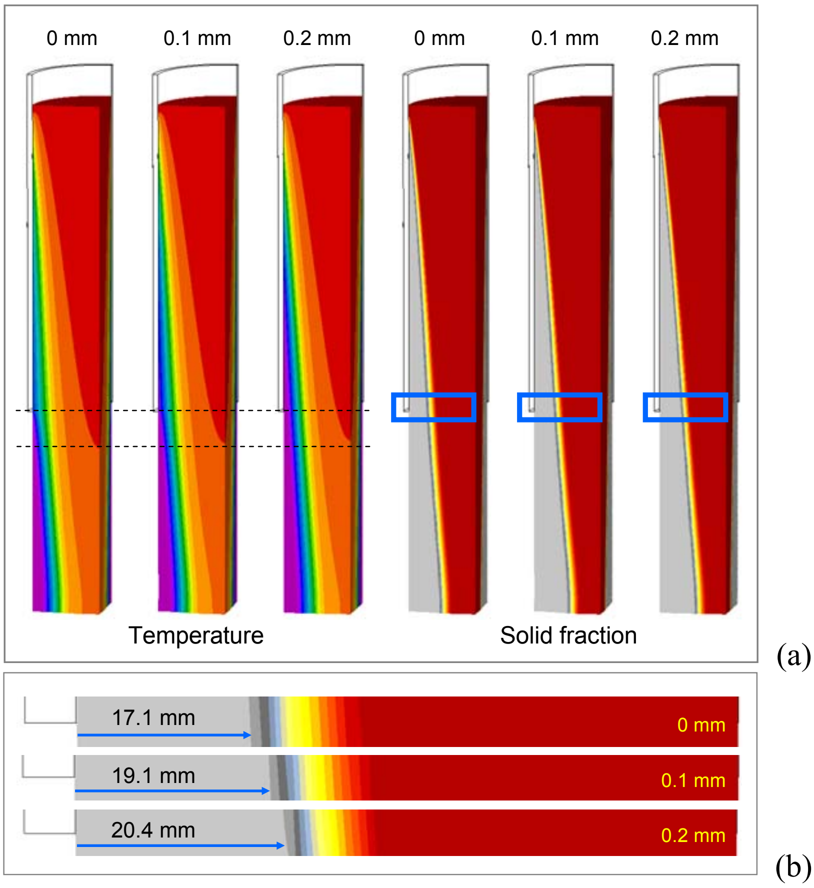


Fig. 14: Temperature and solid fraction in the billet (a) and solid shell thickness (b) in a cross-section at the mould exit, for different tapering values.

Figure 14 shows the consequence of gap formation on the thermal behaviour in the billet. The liquid pool is deeper when there is no tapering because of the significant gap. Also, in (14b), one can see the effect of tapering on the solid shell thickness at the mould exit (i.e. in the cross section for the zone surrounded by a blue rectangle in 14a). After these results, it appears that for this case, a tapering of 0.2 mm is the optimal mould design to keep a good thermal contact (a more important taper would require more deformation of the ingot, as in extrusion).

4. CONCLUSIONS

The present paper demonstrates the wide capabilities of numerical modelling for continuous casting application. The ProCAST software can address different aspects of this complex process using appropriate approaches and algorithms. Thus, the solid transport method can be used to treat steady state phenomenon like thermal-flow behaviour for a curved ingot in the permanent regime, whereas non-steady state approaches should be used when the thermal history of the metal plays a significant role in the problem that needs to be addressed. In particular, the new MiLE algorithm is well suited for the study of transient thermal and fluid flow regimes and also stresses formation during solidification and cooling. Various examples have been presented to illustrate how ProCAST can help the finding of better process parameters or design for continuous casting. Finally, it should be pointed out that other models like the cellular automaton model for grain structure prediction (CAFE, see [2]), Advanced gas shrinkage Porosity Model (APM, see [3]) or Hot Cracking Sensitivity (HCS, see [4]) can be used in conjuction with thermal, flow and stress calculations.

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