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Some Results on Neutral Modelling of the Steel Continuous Casting Process

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Abstract

The modelling goal is to obtain a neutral representation of the process with enough information to generate qualitative information about the behaviour of the process. Such a representation must be able to change models on different levels among the user's world. The obtained models have physical structure and parameters, under declarative and neutral format, as the Modelica modelling language provides. The behaviour of the models is obtained by considering and properly modelling the basic phenomena running on different modelling levels. More sophisticated models could be obtained by adding more knowledge and information at the place where the model is used of.
Keywords: Process Modelling; Neutral modelling; Metamodelling; Continuous casting; Modelica.

1. Introduction

The considered process is steel continuous casting. Most previous advances in continuous casting modelling have been based on empirical knowledge gained from experimentation with the process. Such models are mainly equation based and describe only parts of the process. Meanwhile model exchange among different simulation environments is a strong and real need. No model can reveal all the phenomena running within a process.

The modelling goal is to obtain a neutral representation of the process. Such a model must have enough information to generate qualitative information about the behaviour of the process. A more sophisticated model could be obtained by adding more knowledge and information at the place where the model is used.

The model has a physical structure and is based on running phenomena, which have measurable parameters and physical meanings, e.g. temperature, pressure, volumetric flows. The modelling framework is based on Modelica, which is a very promising standard in neutral modelling [1], [2], especial for very complex processes, like the considered process.

The physical process is described in section 2. Its description is made at the physical level and based on the involved phenomena. The methodology of modelling is presented using metamodelling concepts presented and described in section 3. Three basic sub-models are considered in this work, based on physical decomposition of the process: the ladle, the tundish and the cooling model. Each of these models is considered by describing and modelling separately for validation purposes. It is the scope of sections 4, 5 and 6. Finally, in the section 7, some simulation results are presented and discussed.

2. Description of the Process

In the continuous casting process, molten material (metal) is delivered from the bottom of a transfer vessel (the tundish) into a mold cavity. Here, the water-cooled walls of the mold extract heat to solidify a shell that contains the liquid pool. The shell is withdrawn from the bottom of mold at a "casting speed" that matches the inflow of metal, so that the process ideally operates at a steady state. Below the mold, water sprays extract heat from the surface, and the strand core eventually becomes fully solid when it reaches the "metallurgical length".

Heat flow and solidification phenomena models are used for basic design and troubleshooting of this process. Heat transfer in the mold region is controlled mainly by heat conduction across the interface between the surface of the solidifying shell and the mold. In steel slab casting operations with mold flux, such models feature a detailed treatment of the interface, including heat, mass, and momentum balances on the flux in the gap and the effect of shell surface imperfections on heat flow [3]. Heat flow models which extend below the mold are needed for basic machine design to ensure that the last support roll and torch cutter are positioned beyond the metallurgical length for the highest casting speed. Below the mold, air mist and water spray cooling maintain surface temperature of the strand, while the interior solidifies.

Continuous casting involves a staggering complexity of interacting phenomena at the mechanistic level. Some of the important phenomena include, [4], [5], [6], [7], [8], [9], [10], [11], and [12]:

- fully-turbulent, transient fluid motion in a complex geometry (inlet nozzle and strand liquid pool), affected by argon gas bubbles, thermal and solute buoyancies;
- thermodynamic reactions within and between the powder and steel phases;
- dynamic motion of the free liquid surfaces and interfaces, including the effects of surface tension, oscillation and gravity-induced waves, and flow in several phases;
- thermal, fluid, and mechanical interactions in the meniscus region between the solidifying meniscus, solid slag rim, infiltrating molten flux, liquid steel, powder layers, and inclusion particles;
- heat transport through the solidifying steel shell, the interface between shell and mold, (which contains powder layers and growing air gaps) and the copper mold;
- solidification of the steel shell, including the growth of grains and microstructures, phase transformations, precipitate formation, and microsegregation;

Because of this complexity, no model can include all of the phenomena at once. An essential aspect of successful model development is the selection of the key phenomena of interest to a particular modelling objective and by making of reasonable assumptions. The basic phenomena considered in this work are related to heat transfer among material's phases and flow of the processed material.

Mechanistic models are based on satisfying the laws of conservation of heat, mass, force and momentum in an appropriate domain with appropriate boundary conditions. In this work, each considered phenomenon is represented by term(s) in these governing equations, excepting the force and momentum.

Other phenomena can be ignored or incorporated using empirical constants, obtained through experimentation and model calibration.

3. The modelling methodology

Following the above hypothesis the phenomena from two domains were considered: thermal and fluid phenomena. In the thermal domain the considered phenomena are conduction and radiation. From the fluid domain, fluid flow is considered as effect of difference pressure. For each domain, ports (some time interfaces called) must be defined, in order to describe the quantitative behaviour of the process and to write mass and energy balances.

By metamodel is understood a model of the modelling methodology. From the methodology point of view two metamodels are presented in Fig.1 and Fig. 2. The first metamodel shows the highest point of view of the methodology. The process model in considered being an aggregation of physical model with one or more material models and one or more phenomena models. Material and phenomena models need properties models to compute the thermodynamic and transport properties. The physical model, in association with the properties model, generates constraints related to the behaviour of the model.

The second metamodel is closer to the structure of the model. The process model is composed of two basic models: a phenomena model and a mathematical model. The phenomena model describes the level of the modelling and the interaction among considered phenomena. The quantitative behaviour of the model needs a mathematical model, which depends on the considered phenomena. The mathematical model contains balance and constitutive equations. The interaction of phenomena and mathematical model is described by properly considering ports.

There are two types of ports: external (or static) to describe the input-output flow of the material and internal (or dynamic) to describe the phase transformations of the material during processing. There are two external models, in the sense they could be defined in an independent approach, possible in different (distributed) places and by different modellers. It is the material model and the geometry model.

The material model describes the thermodynamic properties and the interaction of phenomena running on different modeling levels. Based on the context, i.e. the composition of the devices that support the processed material, a model of constraints must be considered and defined.

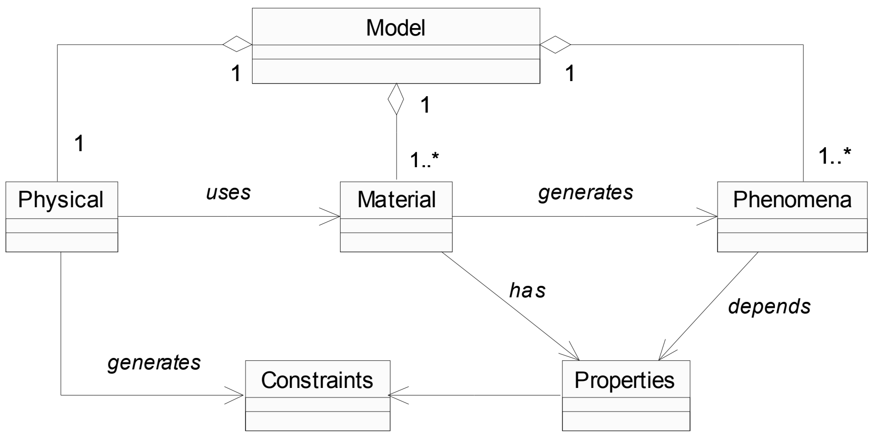

Figure 1: A *partial* metamodel of the process model

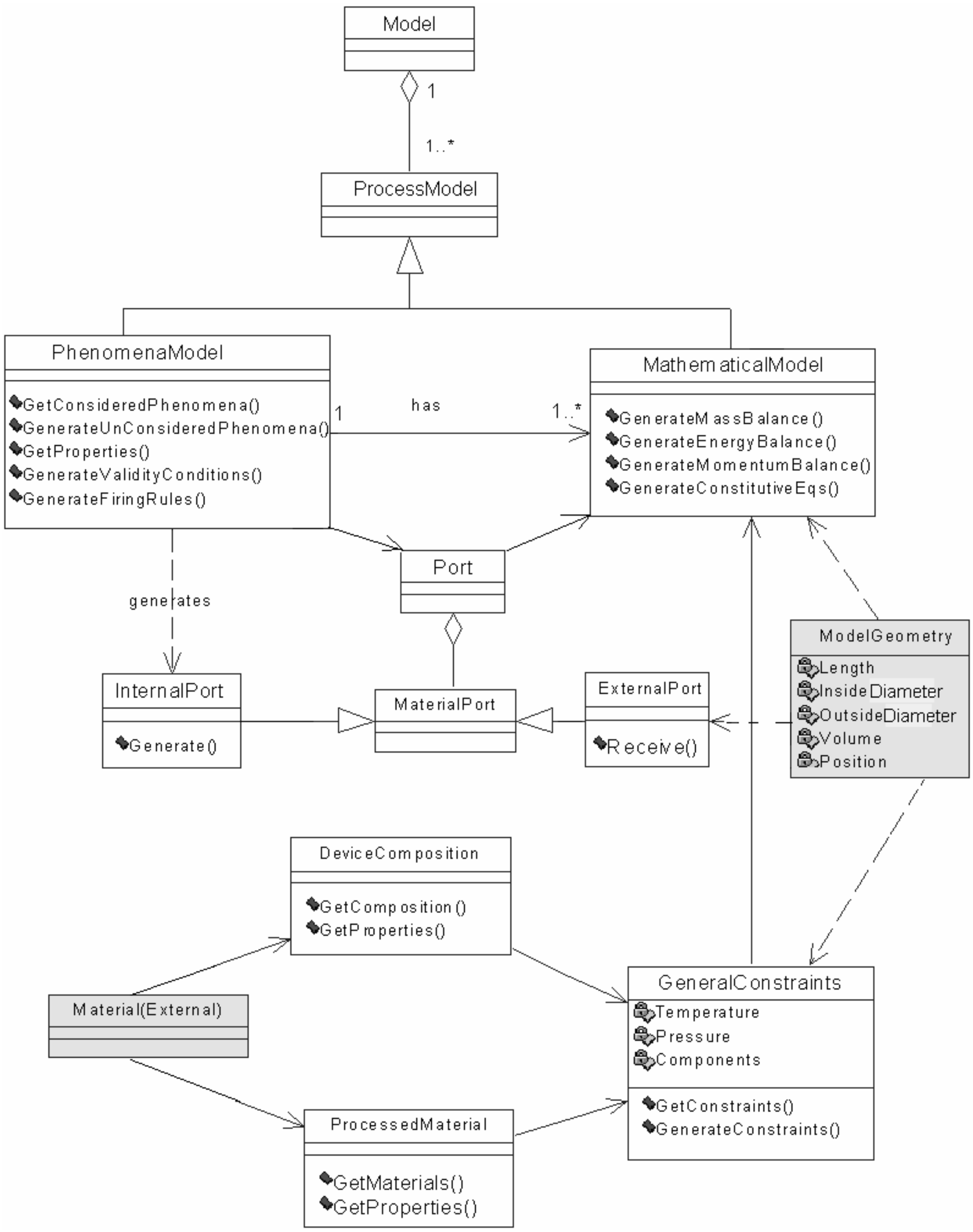

Figure 2: A more detailed metamodel

The constraints model is developed in correlation with the model of the geometry of the plant, where the processing of the material takes place.

Both metamodels are the base of the design a modelling tool, under computed aided modelling environment. Such a tool must assist the modeller to take in account the all the interactions and all necessary phenomena at the considered level of modelling.

4. The model of the ladle

The considered input variable in the ladle is the initial temperature T_0 of the processed material. The necessary phenomena to consider are related to time variation of the temperature inside and outside of the ladle and the variation of steel volume inside of the ladle, when the casting process starts. It is supposed that the steel is in liquid phase and no phase change is performed in the ladle.

Two sub-models cover the ladle: the processed material (steel) and the wall model. The transfer of thermal energy from ladle to outside of ladle is modelled by radiation phenomenon from the surface of the ladle to environment. A valve, conducted by a controller with proper drives, makes the control of the steel debit.

For the considered phenomena the following variables are necessary: temperature and heat flow rate for thermal domain; pressure, temperature and volume flow rate for fluid domain. The interfaces for such phenomena can be defined as:

```
connector PortFluid
        Pressure p;
        flow VolFlowRate qvol;
end PortFluid;

connector PortHeat
        CelsiusTemperature T;
        flow HeatFlowRate qheat;
end PortHeat;

connector PortThermoFluid
        Pressure p;
        CelsiusTemperature T;
        flow VolFlowRate qvol;
end PortThermoFluid;
```

The environment must be taken into consideration in order to show the behaviour of the high temperature sources such as liquid steel. It is expected that the temperature of the environment to rise, near the space of the ladle. Such a model can be as

```
partial model Environment
  PortHeat ha;
  extends EnvironmentProperties;
  CelsiusTemperature T (start=30, min=30);
   parameter Volume vol(start=1000, min=0);
algorithm
   ha.T := T;
equation
   vol * rho * shcap * der(T) = ha.qheat;
end Environment;
```

In the EnvironmentProperties model the properties of the medium related to density, rho, and to specific heat capacity, shcap, are defined.

The phenomena from thermal domain are considered now. It is about of two main phenomena: radiation from the hot surface to another one with a lower temperature; the conduction of heat, which is specific to heat conduction in solid phases. The models can be as:

```
model Conduction
  PortHeat ha,hb;
  ThermalConductivity thermalcond (start = 1e-5);
  Thickness thick (start = 1);
  Area transfer_area (start=1);
   Real Rth(start=1, min=1E-6) "Thermal Res.";
algorithm
   Rth := thick / thermalcond / transfer_area;
   ha.qheat := (ha.T - hb.T) / Rth;
equation
   ha.qheat + hb.qheat = 0;
   // un-defined: thick, thermalcond, transfer_area;
end Conduction;
```

and

```
model Radiation
   PortHeat ha,hb;
   constant Real viewfactor = 0.1 "The view factor";
   constant Real sigma(final
unit="W/(m2.K4)")=5.6704e-8 "Stefan-Boltzman";
   Area transfer_area (start=1, min=0);
   Real Rth(start=1, min=1E-6);
algorithm
   Rth := 1 / sigma / transfer_area / viewfactor;
   ha.qheat := (ha.T^4 - hb.T^4) / Rth;
equation
   ha.qheat + hb.qheat =0;
   // un-defined: transfer_area;
end Radiation;
```

The ladle model contains two sub-models: the wall and the steel. The wall model is composed mainly from a physical model, which defines the size and the composition of the wall, and the steel model. The wall model of the ladle can be as

```
model Wall
   PortHeat ha, hb;
   Conduction hcond;
   Volume vol (start=1);
   Density rho (start=1);
   Real shcap (start=1);
   CelsiusTemperature T (start=30, min=0)"In the
wall centre";
equation
   connect(ha, hcond.ha);
   connect(hb, hcond.hb);
   vol * rho * shcap * der(T) = abs(ha.qheat);
   //re-declare: vol, rho, shcap;
end Wall;
```

The model of the liquid steel is

```
model Steel
   PortHeat ha;
   PortThermoFluid tfb;
   extends SteelProperties;
   CelsiusTemperature T (start=1500);
   Volume vol(start=1, min=0);
   Area area (start=1, min=0.1);
   Real hout(start=1, min=0)"Enthalpy out-flow";
algorithm
   hout := tfb.qvol * shcap * rho * tfb.T;
   tfb.p := 1 + vol * rho * 9.8 /101325 /area;
   tfb.T := T; ha.T := T;
equation
   der(vol) = tfb.qvol;
   rho * vol * shcap * der(T) = hout + ha.qheat;
end Steel;
```

Now, the ladle model can be defined as

```
model Ladle
   PortHeat ha;
// interaction with env. near the steel surface;
   PortHeat hb;
// interaction with tundish;
   PortThermoFluid tfc;
// phenomena models:
   Wall wall;
   Steel steel;
// inherits from:
   extends LadleGeometry;
   extends LadleMaterialProperties;
   Real h(start=1)"Steel heigth inside ladle";
algorithm
  h := steel.vol / ladle_area;
   wall.hcond.transfer_area := ladle_lateral_area;
   wall.hcond.thick := ladle_thick;
   wall.hcond.thermalcond := ladle_kL;
   wall.shcap := ladle_speccap;
   wall.vol := ladle_vol;
   wall.rho := ladle_rho;
   steel.area := ladle_area;
equation
   connect(wall.ha, ha);
   connect(wall.hb, steel.ha);
   connect(steel.ha, hb);
   connect(steel.tfb, tfc);
end Ladle;
```

The valve is considered as linear and with a very small resistance. The model is

```
model Valve "A model for valve"
   PortThermoFluid tfa,tfb;
   PortControl ca;
   parameter Real res(start=0.1, min=1e-6);
   Boolean off;
algorithm
   off = ca.u < 0;
equation
    tfa.qvol = if off then 0 else (tfa.p-tfb.p)/res;
    tfa.qvol + tfb.qvol = 0;     tfa.T = tfb.T;
end Valve;
```

5. The model of the tundish

The input variable in the tundish model is the volume flow and the steel height inside of the tundish is the controlled variable. The basic phenomena are related to the flow of materials from ladle to tundish. Because no phase transformations are taking place, for the material model is necessary to have only a model for the liquid phase. The interaction with the environment is made by the lateral surface of the tundish only.

The model and some submodels are presented in the Fig. 3. The test model is composed from the tandem ladle plus tundish, completed with material source, (“source”), valves for events (“valve1”, “valve2”), and a load model (“load”). Inside of the dot lines polygons the sub-models of ladle and tundish were presented. In the following the models will be presented and discussed.

The ladle and the tundish have the same structure. Both use a material model (steel) and a wall model.

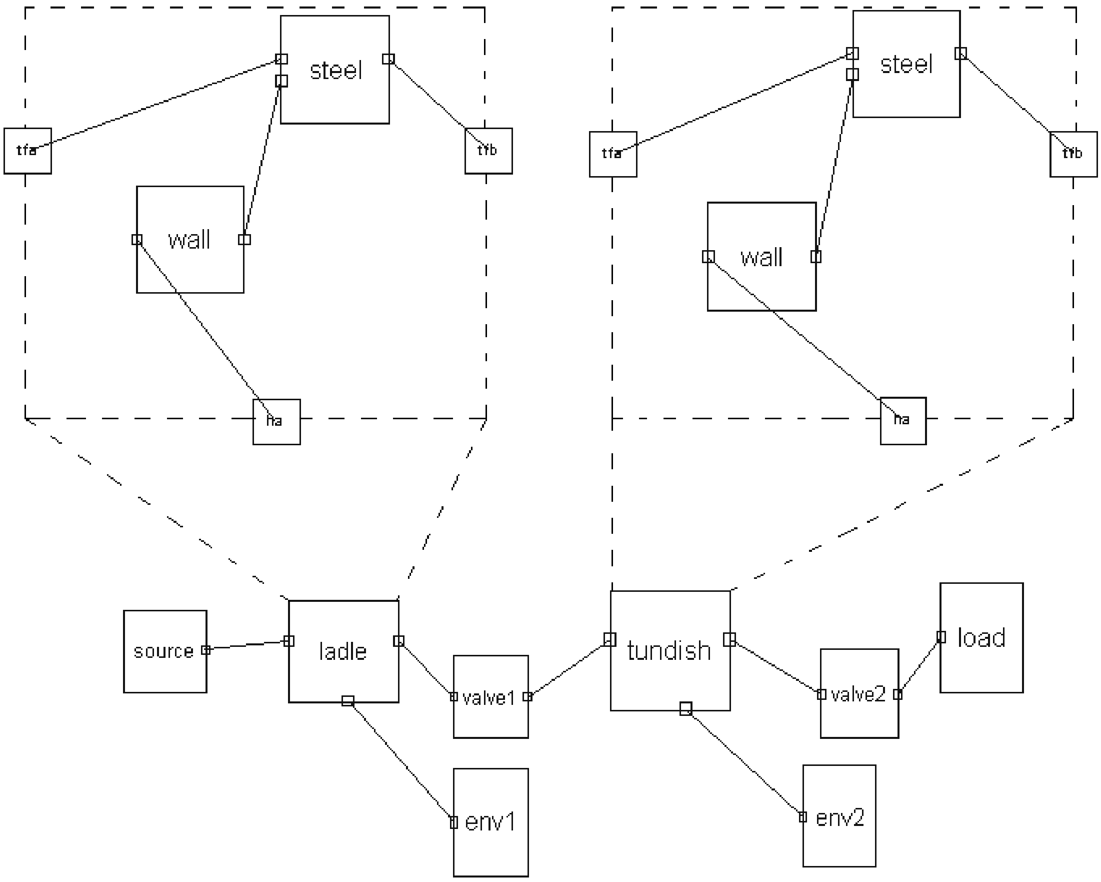

Figure 3: The test structure for the ladle-tundish tandem

The wall sustains the steel. The model of the processed material is called Steel. It has two thermo-fluid ports and one heat port. The first two are necessary to model the flow of the steel. The heat port is necessary to model the interaction with the wall.

The Steel model must be improved by adding a ThermoFluid port to model the input and the output flows of the material in tundish:

```
model Steel
  PortThermoFluid tfa,tfb;
  PortHeat ha;
// parameters from steel properties model;
  parameter Density rho(start=1000);
  parameter SpecificHeatCapacity shcap(start=1e-5);
  CelsiusTemperature T (start=1500);
  Volume vol(start=1, min=0.1, max =10);
  Enthalpy hin(start=1, min=0)"Enthalpy in-flow";
  Enthalpy hout(start=1, min=0)"Enthalpy out-flow";
  Area press_area(start=1, min=0.1) "Area for grav. pressure";
equation
  hin = tfa.qvol * shcap * rho * tfa.T;
  hout = tfb.qvol * shcap * rho * tfb.T;
  der(vol) = tfa.qvol + tfb.qvol;
  vol * rho * shcap *der(T) = hout + hin + ha.qheat;
  T = tfb.T;  ha.T =T;
// un-defined: press_area, tfa.p, tfb.p; (context dependency!);
end Steel;
```

The steel model is considered with volumic and material properties. The pressures on two ports will be defined later when the geometry of the vessel that sustains the steel is defined. It is about of context details. The model of the wall must define the geometry, the material properties and the heat conduction phenomena, as:

```
model Wall
  PortHeat ha, hb;
// parameters from wall material properties;
  ThermalConductivity thermalcond (start=1e-5);
// parameters from geometrical wall model;
  Thickness thick (start=1);
  Area hcond_transfer_area (start=1);
  Density rho(start=1);
  Volume vol (start=1);
```

```
   SpecificHeatCapacity shcap(start=1);
   Real Rth(start=1, min=1E-6) "Thermal resistance";
   CelsiusTemperature T (start=100);
equation
   Rth = thick / thermalcond / hcond_transfer_area;
   ha.qheat = (ha.T - hb.T) / Rth;
   T = if ha.qheat > 0 then hb.T else ha.T;
   vol * rho * shcap *der(T) = ha.qheat + hb.qheat;
 //un-defined: vol, rho, shcap, thermalcond, thick,
hcond_transfer_area;
end Wall;
```

The tundish model says that the tundish (object) an interaction between the wall and steel behaviour. The declarative model can be as

```
model Tundish
   PortThermoFluid tfa, tfb;
   PortHeat ha;
//  parameters from tundish geometry model:
   parameter Height tundish_h (start=1);
   parameter Thickness tundish_thick (start=0.5);
   parameter Volume tundish_vol(start=5, min=0.1);
   parameter Diameter tundish_d (start=1, min=0.1);
  Area tundish_area (start=1, min=0.1)"Hor.Cross-
section area";
   Area tundish_lateral_area (start=1, min=0.1);
//  parameters from tundish material properties:
   parameter ThermalConductivity tundish_kL;
   Real steelh(start=1)"Steel heigth inside tundish";
   Wall wall;
   Steel steel;
algorithm
   tundish_area := tundish_vol / tundish_h;
   tundish_lateral_area=3.14*tundish_d*tundish_h;
   steelh := steel.vol / tundish_area;
   wall.hcond_transfer_area := 3.14 * tundish_d
* steelh;
    wall.thick := tundish_thick;
   wall.thermalcond := tundish_kL;
   wall.rho := 2000;
   wall.vol := 1;
   wall.shcap := 0.9;
   steel.press_area := tundish_area;
equation
// context definition:
   steel.tfb.p = steel.tfa.p + steel.vol * steel.rho * 9.8
/101325 / steel.press_area;
   steel.tfa.p =1;
   connect(wall.hb, ha);
   connect(wall.ha, steel.ha);
   connect(steel.tfa, tfa);
   connect(steel.tfb, tfb);
end Tundish;
```

6. The cooling model

The phenomena running after tundish can be considered as generated by a single type model: a cooling model of the liquid material. From a phenomenological point of view, it should model the transfer of energy from the liquid and the solid phase of the processed material to other material that acts as receptor or loads of the thermal energy.

The difficulty of the modelling problem is from the uncertainties generated by the material parameters, by the phenomena interactions during the casting process. More, all parameters are distributed and are temperature dependent. Moreover there are many material phase transformations such as:

- liquid-solid transformation of the processed material;
- liquid-solid-gaseous bidirectional transformations of the auxiliary materials, which allow the lubrification of the processed material in the primary cooling zone;
- liquid-gaseous phase transformations for the fluid materials that take the thermal energy of the solidified material and make the secondary cooling.

Taking in account such a complex set of phenomena, a simplified model will be considered based on balance energy. This approach is started also from the reality that in the real installation the information for control and monitoring purposes use global variables, e.g. volume flow rates and temperatures of the involved materials, and not local variables, like densities and viscosities.

In Fig. 4 the structure of the cooling models is presented. There are also represented the sources of the materials and materials loads. The structure of the cooling model is represented in the upper left side of the Fig. 4. Three models are considered: two of materials (Steel and Water) and a model for separation (Wall).

On the upper right side the structure of the processed material is presented, as interaction of two submodels: material in liquid phase (Liquid Steel) and material in solid phase (Solid Steel). For these two phases interfaces were defined: *tfla*, *tflb* for liquid phase and *tfsa, tfsb* for solid phase.

The processed materials have material interfaces *(tfa, tfb, tfc*) and interfaces for changing of the thermal energy (*ha*), as it is presented in the lower right side.

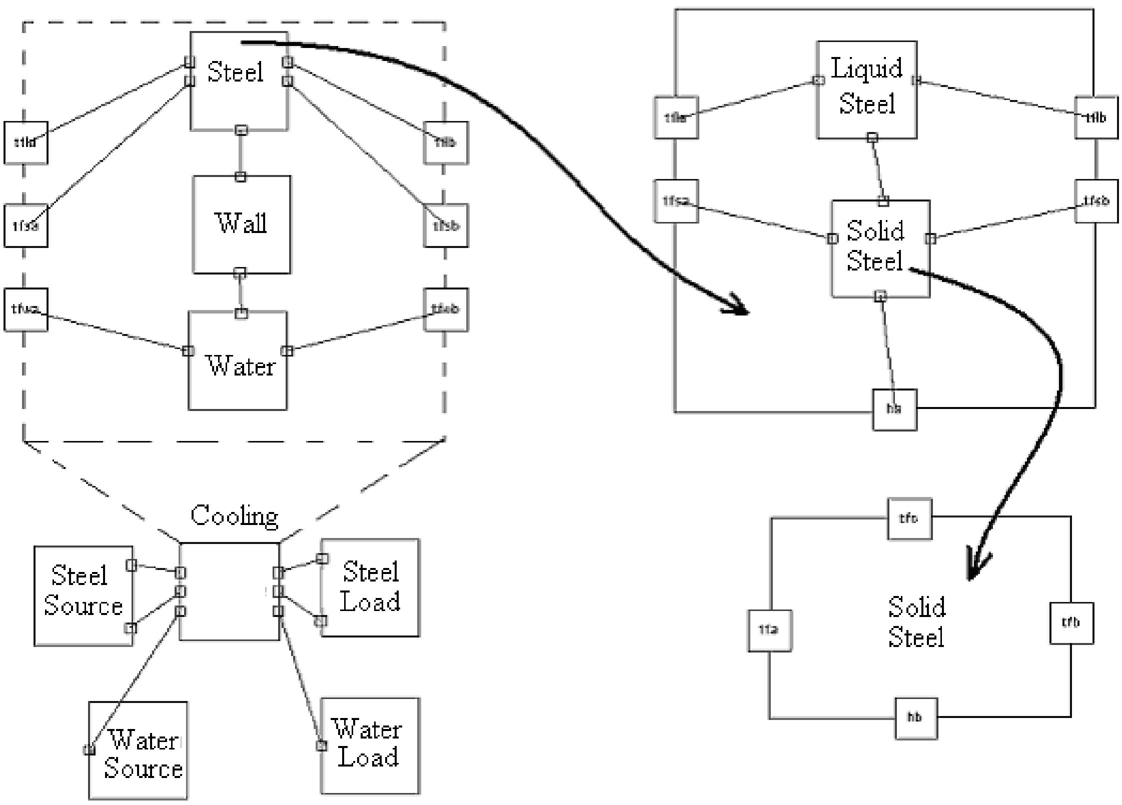

Figure 4: The structure of the cooling model
for the continuous casting of the steel using water as cooling agent

The cooling model is designed with the same structure in order to be able to use in both sides of the cooling zones: primary and secondary. Setting up the numerical values of input-output variables, makes the selection of one of them. By example, for the primary cooling zone zeros values are necessary for the solid materials, because the material in received from tundish with liquid phase only. In the following the model of the processed material will be described, as interaction between solid and liquid phase. The model for the solid phase is

```
model SteelSolid “The SteelSolid model”
   PortThermoFluid tfa,tfb, tfc;
   PortHeat hb;
   extends SteelSolidProperties;
   CelsiusTemperature T (start=30);
   Volume vol(start=1, min=0.1);
   Enthalpy hin1(start=1"In-flow from source side";
   Enthalpy hin2(start=1)"In-flow from liquid side";
   Enthalpy hout(start=1)"Out-flow";
equation
   hin1 = tfa.qvol * shcap * rho * tfa.T;
   hin2 = tfc.qvol * shcap * rho * tfc.T;
   hout = tfb.qvol * shcap * rho * tfb.T;
   vol*rho*shcap*der(T)=hout+hin1+hin2+hb.qheat;
   tfb.T = T;
   hb.T = (tfa.T + tfb.T + tfc.T)/3;
   // undefined: vol;
   end SteelSolid;
```

The model for the liquid phase is

```
model SteelLiquid “The SteelLiquid model “
   PortThermoFluid tfa,tfb, tfc;
   Extends SteelLiquidProperties;
   Temperature T (start=1500);
   Volume vol(start=2, min=0.1);
   Enthalpy hin(start=1)"In-flow from source side";
   Enthalpy hout1(start=1)"Out-flow to next block";
   Enthalpy hout2(start=1)"Out-flow to solid steel";
   Enthalpy H(start=1) "Latent energy";
equation
   hin = tfa.qvol * shcap * rho * tfa.T;
   hout1 = tfb.qvol * shcap * rho * tfb.T;
   hout2 = tfc.qvol * shcap * rho * tfc.T;
   H = vol * rho * L;
   der(vol)=if vol>0 then tfa.qvol+tfb.qvol+tfc.qvol
else 0;
   vol*rho*shcap*der(T)=hin+hout1+hout2- der(H);
   tfb.T = T;
end SteelLiquid;
```

The model for the processed (cooled) material is

```
model Steel "The Steel model"
   PortThermoFluid tfla, tflb;
   PortThermoFluid tfsa, tfsb;
   PortHeat ha;
   SteelLiquid sliquid;
   SteelSolid ssolid;
   Volume vol(start=3, min=0);
   parameter Real K (start=1e-8) "L2Solid speed";
algorithm
   ssolid.tfc.qvol := K * sliquid.H;
equation
   connect(tfla, sliquid.tfa);
   connect(sliquid.tfb, tflb);
   connect(ssolid.tfa, tfsa);
   connect(ssolid.tfb, tfsb);
   connect(sliquid.tfc, ssolid.tfc);
   connect(ssolid.hb, ha);
   sliquid.vol + ssolid.vol = vol;
   ssolid.tfc.T = if sliquid.vol > 0 then sliquid.Ts else
ssolid.T;
// un-defined: vol; context dependent;
end Steel;
```

Finally, the cooling model considers the interaction between the model of the processed material (steel) and the material that takes the energy in order to be able to transform the processed material from liquid to solid phase. The cooling model is as

```
model Cooling
  PortThermoFluid tfla, tflb "Steel Liquid";
  PortThermoFluid tfsa, tfsb "Steel Solid";
  PortThermoFluid tfwa, tfwb "Water";
// from geometry model;:
  parameter Real Rfluid (start=1) "Thermal res";
  parameter Area area (start=1)"Heat Transfer area";
  Water water; Steel steel;   Wall wall;
equation
  connect(steel.tfla, tfla);
  connect(steel.tflb, tflb);
  connect(steel.tfsa, tfsa);
  connect(steel.tfsb, tfsb);
  connect(steel.ha, wall.ha);
  connect(wall.hb, water.ha);
  connect(water.tfa, tfwa);
  connect(water.tfb, tfwb);
  steel.vol = 3;       // real volume must be defined;
  water.vol = 0.5;  // real volume must be defined;
end Cooling;
```

7. The casting model

The casting model is composed from three main submodels or modules: the ladle, the tundish, and the cooling model. In the simulation scenario two other models are necessary, i.e. the source of the steel, which impose the events in changing the liquid material on the input of the process, and, the second, the load models which is responsible for the reference of the casting speed. The declarative model can be as

```
model TestCastingProcess
  SourceSteel steel_S;
  Ladle ladle; Tundish tundish;
  Cooling cool;
  WaterSource water_S;
  WaterLoad water_L;
  LoadSteel load_S;
equation
  connect(steel_S.tfla, ladle.tfla);
  connect(ladle.tflb, tundish.tfla);
  connect(tundish.tflb, cool.tfla);
  connect(water_S.tfa, cool.tfwa);
  connect(cool.tfwb, water_L.tfa);
  connect(cool.tflb, load_S.tfla);
  connect(cool.tfsb, load_S.tfsa);
  connect(cool.tfwb, water_L.tfa);
end TestCastingProcess;
```

Fig.5 presents the evolution of the steel temperatures in ladle and tundish. The simulation scenario supposes that from time to time, when the temperature is increasing in steps, the ladle is filled up with new liquid material.

Conclusions

The main goal of the work was to obtain a neutral representation of the continuous casting process of the steel. Considering all aspects of the process is out of the scope and is quite difficult without a base library of materials and phase transformation under neutral format.

It was supposed that the neutral model is the start point in the development of more sophisticated and more accurate models and it is used as a first description of the process. Some aspects of the modelling methodology using Modelica language were also presented.

The models for ladle, tundish and cooling zone were presented. Simulation results are presented also in order to check the right qualitative behaviour of the obtained models, under an imposed scenario at the input of the casting process. The results are accurate regarding on the evolution of the temperature of the steel inside the tundish.

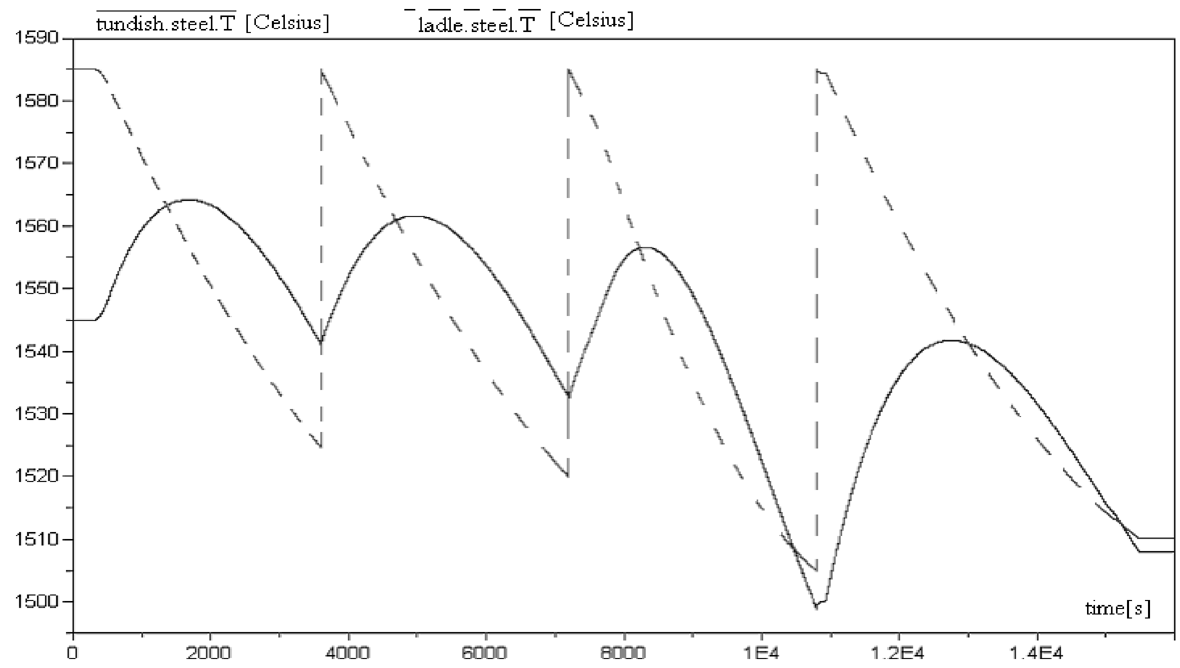

Figure 5: Temperature evolution of the steel in ladle and tundish

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