Modelica model of industrial gas furnaces

Iñigo Aranburu[1,*], *Bakartxo* Egilegor[1], *Iñigo* Bonilla[1], *Jaio* Manzanedo[1], and *Haizea* Gaztañaga[1]

[1]IKERLAN Technology Research Center, 20500, Arrasate, Spain

Abstract. Modelica models for the prediction of the temperature of the load inside a walking basket type reheat furnace of the aluminium industry have been developed. The loads move through the furnace with discrete movements. Several library components have been developed using the Modelica Standard Fluid Library. In order to validate them a full 1D furnace simulation model has been built. It allows calculating the heat transfer through walls, the temperature and the composition of combustion gases, the temperature of the aluminium products, as well as the fumes flow and the pressure drops. The library provides the necessary resources for modelling this type of furnaces flexibly and quickly. The objective of the work is to validate Modelica as analyse tool for evaluating the different possibilities of heat recovery in this kind on furnaces.

1 Introduction

The efficient and sustainable use of energy is currently a social obligation. The aluminium industry incorporates processes that are large consumers of energy as, for example, the solubilisation and ageing of aluminium parts. They are carried out in gas furnaces with high energy losses through fumes. The measures for saving energy in these processes often involve a risky redesign of the installation since they usually operate at full capacity. Any error has a high cost, so these measures are not being introduced in practice [1]. It is, therefore, necessary to have tools that allow analysing and evaluating the different modes of operation of these furnaces. Dynamic and precise computer simulation models that can be easily adapted are necessary. In this paper, we show the work that we are doing in this line. For that, we have chosen an open-language standard, Modelica, and a commercial simulation environment, Dymola.

This task is being done under ETEKINA project [2], that is an EU funded research project aiming to recover the waste heat stream in energy-intensive industries using heat pipe technologies. The final target of our work is to develop a Modelica library that includes submodels of heat and mass transfer, as well as, other complex entities such as load movement controller, sensors, actuators and controls, which together will allow building quickly a full cyber-physical model of an industrial gas furnace.

---

[*] Corresponding author: iaramburu@ikerlan.es

2 Basic considerations

To validate Modelica as an analysis tool, that allows assessing different heat recovery solutions, we have chosen a real case of an aluminium ageing furnace. This furnace is part of a broader thermal treatment system described in [3], and that we show in Fig. 1. In the future, it will be completed with an energy recovery system based on heat pipe technology.

2.1 The current furnace

A repeated structure (from now on "modules") forms the ageing furnace. The number of times that is repeated depends on the process, but it can typically be 6 or 7. The parts that must be treated are placed in baskets forming a batch of loads. Each module defines a specific position for the baskets. These enter the furnace through the first module and exit through the latter, advancing one module in each period. They remain inside the module, at a precise temperature, for exact time.
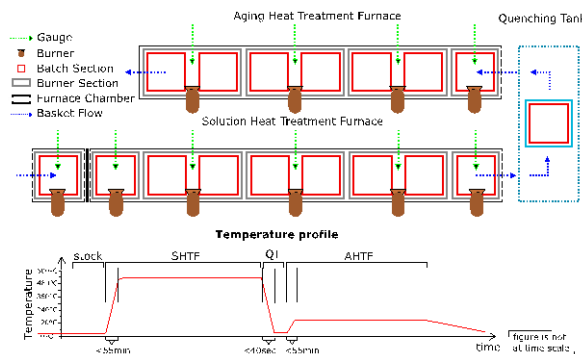

Fig. 1. Solubilisation and ageing process in a continuous installation of aluminium industry [3].

The modules are grouped in control zones formed by one or two of them. Inside, the temperature and heating rate is controlled. The temperature control is carried out using a natural gas burner, with a PID controller acting over the gas flow. The combustion air is kept constant with high excess air. The ageing temperature setpoint is 160°C. A large centrifugal fan generates a strong recirculation, mixing the burner combustion fumes with those that return from the load. The uniformity of temperatures inside the furnace is +/- 3°C. Except in the area of the burner, heat transfer occurs mainly by convection. An exhaust duct directs the fumes to a natural draft chimney. The infiltration of outside air is a typical problem of these facilities.

2.2 The tool

To simulate this furnace by a computer, the main physical phenomena that we must take into account are:
- the thermal inertial, formed by the load and the furnace structure;
- the convection heat transfer, from the fumes to load and the furnace structure;
- the conduction heat transfer, through walls and ground;
- the combustion heat and fumes generation;
- the air and fumes transport, from the furnace to the chimney exit;
- the transport of loads through the furnace (called "solid flow");

    –   the outdoor air infiltrations, and

    –   the control of the temperature of the fumes.

The simulation of the movement of the fumes inside the module, generated by the internal fan, is very complicated. It does not contribute much more than the estimation of the internal convection coefficients. A 3D model and computational fluid dynamic solver could be used to simulate it. However, it could hardly solve the system as a whole with sufficient agility to carry out a comparative study. For all this, we decided to consider each module as a volume, with an ideally mixed gas, and perform a 1D simulation model of the entire system. We choose Modelica and Dymola for this task.

Modelica is an open source modelling language that allows building mathematical models of complex physical systems that evolve over time. It is an object-oriented equation based programming language that enables an *acausal* system modelling. On the other hand, Dymola is a commercial modelling and simulation environment based in Modelica.

We have programmed directly in Modelica the components involved in the solid flow. To simulate the 1D behaviour of the fluid components like valves or pipes, we have used the fluid library, included in the Modelica Standard Library (MSL). A complete description of the equations involved in this fluid library is in [4].

3 The model

We used the Dymola graphic interface to build most of the components and the main part of the furnace model. However, in a few times, it has been necessary to code new components directly using Modelica language. The furnace model is configured from physical parameters and can be adapted to different complexity requirements. It consists of four subsystems: Medium, Furnace, Load Controller, and Fumes Extraction System. We want to note that the components of the Modelica fluid library implement the equations of conservation of mass, energy, and momentum, which gives reliability to the model.

3.1 Medium model

One characteristic of the MSL is that the fluid is independent of the components. A model, called *medium*, define the fluid and all its thermodynamic and transport properties. In this application, there are three fluid o gas mixtures: the external air, the natural gas used as combustible, and combustion fumes generated by the burner. In order not to complicate the model we have used the same medium for all of them, an ideal mixture of CH_4, O_2, N_2, CO_2, and H_2O. In each gas entrance, the composition is defined by the mass fraction.

3.2 The furnace

3.2.1 The module

We have based the furnace model on a structure (the module) that represents the internal fumes cavity. The full furnace body is made connecting several modules. The module calculates the state of the fluids, the mass flows (inlets and outlets of combustion fumes, infiltrations of external air) and the heat transfer (walls, baskets, products). We have built several components to simulate walls, loads and other internal elements. They can easily be modified or replaced to simulate different furnaces or different levels of complexity. Each module exchanges hot gases and heat in the form of radiation with the modules to which it is connected. A small pressure drop is added between every two modules to avoid

mathematical singularities at low flow rates. A gas inlet connects the burner that generates the combustion gases. An atmospheric air inlet allows infiltrations caused by the depressurisation generated by the chimney. A thermal connector links each module to each load in the process batch. The model considers the internal volume as a perfect mixture of gases, without differences in pressure or temperature. As we said before, the movement of air, induced by the internal fan, is not simulated. However, the convection coefficients associated to it are included in the model as parameters. They should be calculated from the average air flow rate moved by the recirculation centrifugal fan.
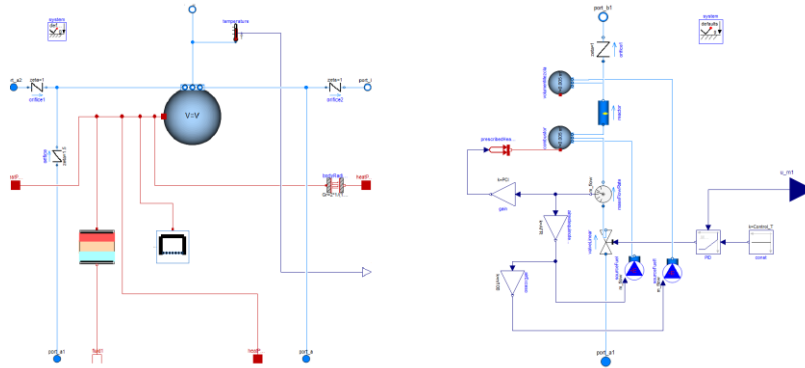

Fig. 2. Modelica furnace submodels. Left: module; Right: burner with PID control.

3.2.2 Burner

This component model the hot fumes generation that heats the furnace. The fumes temperature is approximated by the adiabatic flame temperature, which can be calculated directly by the balance of enthalpies, or from the Low Heating Value (LHV) of the gas. In order not to complicate the simulation in excess, the dynamic of the combustion reaction is ignored, and the composition of the fumes is fixed from the chemical reaction, considering that the methane combustion is complete. So, the burner model is only valid if the air inlet is higher than the stoichiometric air. The first entrance of the combustion model works with zero excess air (stoichiometric combustion); after, secondary air flow is mixed that increases the O2 contents. During this "dilution" the fumes temperature decrease.

3.2.3 Walls

The walls are modelled using Modelica thermal library that gives a one-dimensional solution of heat conduction equations. It is a simple three-layer wall, with the insulation layer in the middle. It is enough to simulate the heat lost by conduction and the thermal inertia of walls. However, if a more detailed model is needed, it can be easily adapted. Two convection blocks model the internal forced convection and the external natural convection heat transfer. Two Modelica connectors (HeatPort) set up the boundary conditions.

3.2.5 Doors

The door model simulates the opening and closing of the furnace doors, calculating the heat lost by radiation and balancing the pressures during the opening. It does not estimate the

losses that are produced by natural convection during openings, so a more advanced model would be needed. However, because the thermal inertia of the air trapped inside the module is minimal in comparison with that of the load, the introduced error is not significant.

3.3 Solid flow model

The solid flow model is the most challenging part of the furnace model. It consists of several different submodels that are shown in figure 3.

3.3.2 LoadModule

The model, called *LoadModule*, defines the load, taking into account the basket and the aluminium parts placed inside it, and calculates their heating. It consists of two submodels: the *Load* and the *ThermalConnector*. The first heats the loads by convection. The convection coefficient is calculated from the fan flow and from some parameters that define the load. It has an input thermal connector that connects it to the *ThermalConnector*. This latter is a virtual submodel that connects each of the loads to each of the furnace modules but only activates one of the connections. In this way, the load and the basket receive energy from a module only if they are positioned inside it.
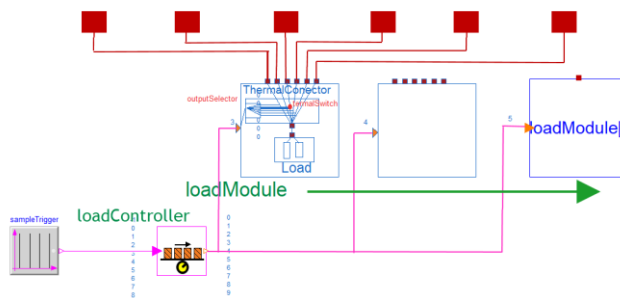

Fig. 3. SolidFlow submodel.

3.3.1 LoadController

The *LoadControler* calculates the positions of the loads as well as the heat transfer between those and the furnace modules according to their respective positions. It assigns one position to each load forming a queue or input buffer. The number of loads must be set before starting the simulation, and it determines how many load objects are present in the processing batch. When it receives an external periodic signal from a pulse generator, it moves the batch and all loads advancing one step. If one of them exits from the furnace, it stops receiving or losing heat.

3.3 2. Thermal Valve

This model works similarly to a fluidic valve, controlling the passage of heat as a function of an input signal. It allows controlling the flow of heat so that a load only receives heat from a module if it is inside.

3.4 Fumes extraction system

The fumes extraction system is built from components of Modelica fluid library. The non-linearity of these components can, in some cases, make the solving of the equations difficult, so it is preferable to make as many simplifications as possible. The fume extraction of the ageing furnace is a system of a natural draft in which the fumes come out through a long chimney. The balance of mass, energy and moment, included in the equations of the components, allow chimney draft simulation by just defining the pressure contour conditions correctly. The depressurisation caused by this draft inside the furnace results in infiltrations of outside air and an efficiency loss.
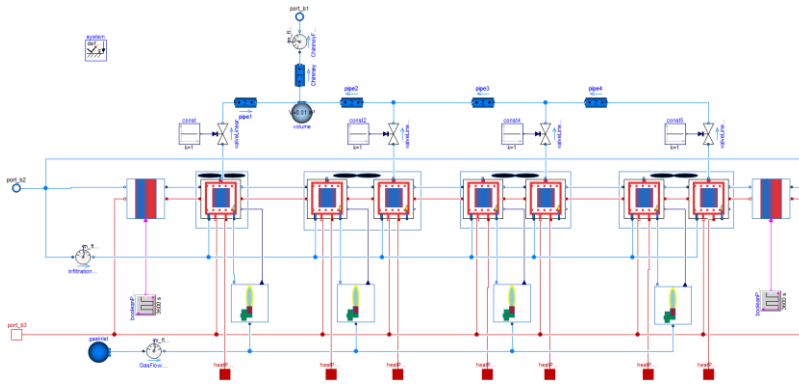
Fig. 4. Ageing furnace submodel showing four control zones and seven positions/modules.

4 Simulation. Testing the heat transfer models

4.1 Experimental setup

The developed models are tested simulating the behaviour of the ageing furnace described in section 2.1. It consists of 7 heating modules grouped into 4 control zones. A natural gas burner that works with fixed excess air heats each control zone. A PID control acts on the gas flow to regulate the thermal power. The fumes are extracted by natural draft through 4 extraction points which lead them to a chimney of 14 meters height. The furnace has a length of 11.4 meters. The walls have 2 metal sheets and an insulating layer between them.

4.2 Simulation

For the simulation, the number of loads is set to 10. The solid flow model fixes the initial positions and temperatures of them. Each load consists of 2 steel baskets with 156 aluminium cylinders with a total mass of 1140 kg. A PID control regulates the energy input of each burner. The natural gas LHV is set at 48.9 MJ/kg. The high excess air remains constant during the simulation with a temperature of 20°C. The movement of load starts after 1800 seconds. Every 3600 seconds the doors open and the loads move one step in the furnace. The Dassl integration algorithm is used. The integration time for simulation of 25700 seconds was 25 seconds.
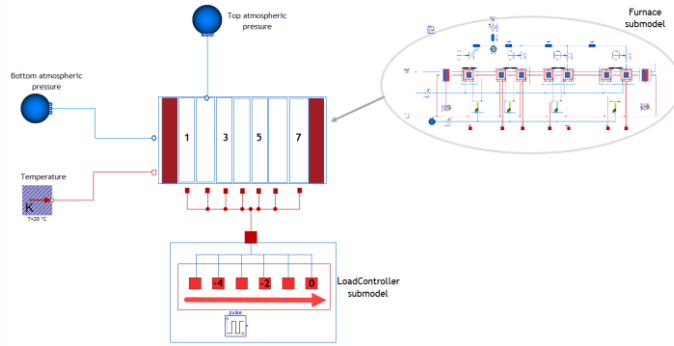
Fig. 5. Full furnace model with fumes exhaust by chimney and bath load controller.

4.3 Results

The figures that follow show a small part of the results. Figure 6 shows the position of loads 1, 3, 5 and 7 as a function of time. The position 1 corresponds to the first module of the furnace, and the position 7 to the last. The initial load positions range from 0 to -9.
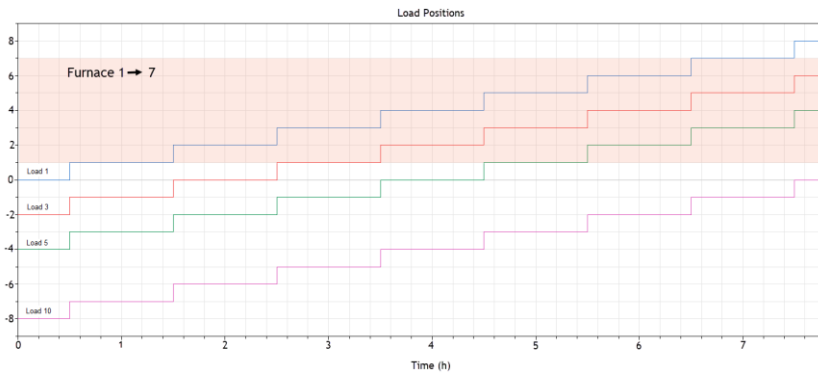

Fig. 6. Positions of loads 1, 3, 5 and 10.

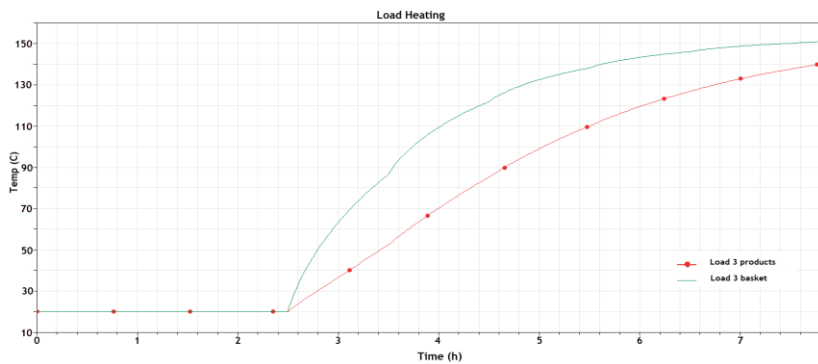Figure 7 shows the heating of load number 3 which enters inside the furnace after 9.000 seconds.

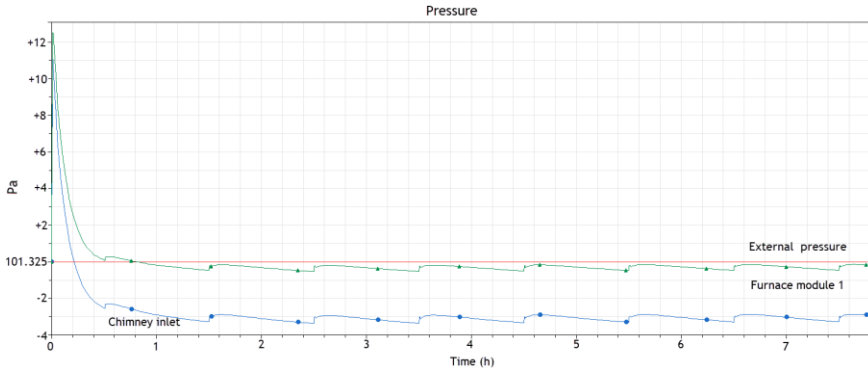**Fig. 7.** Temperature of load 3.

Fig. 8. Pressure distribution.

Figure 8 shows the pressures inside module 1, at the entrance to the chimney. The atmospheric pressure outside the furnace is 101.325 pascal, and at the exit of the chimney is 101.165 pascal (not shown). It can be observed how initially, when the burners start, a positive pressure is generated that becomes negative when the chimney draft arises. Figure 9 shows the behaviour of the furnace and the loads during a verification test. The burner 1 is controlled by a proportional control with a set point of 160°C; the rest of the burners introduce combustion fumes at 160°C. The temperatures of the modules 2 to 7 (only module 2 is shown) and the temperature of the load 1, after its pass through the furnace, are stabilised at 137°C. The figure also shows the gas consumption of the burner 1.
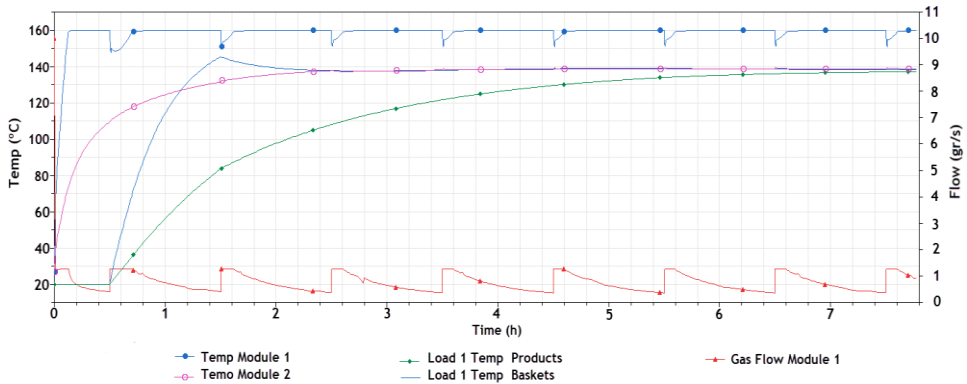

Fig. 9. Furnace temperatures and gas flow.

5 Conclusion

Some Modelica components have been developed to simulate the transfer of heat and mass in thermal treatment furnaces of industrial plants, in which the loads move forward through the furnace with discrete movement. The simulation of a test shows satisfactory results. The physical phenomena of the process, such as chimney draft, outside air infiltration or load heating are correctly simulated. The built furnace model is sufficiently precise and fast enough to perform a comparative analysis between different heat recovery measures and control solutions. It is particularly suitable for designing advanced control concepts. The next task is to modify its parameters with the correct values of the furnace under study and to compare different control concepts. The developed model provides practical information

about the furnace's performance under alternative control concepts and designs before actual implementation.

References

1. T. D. Gerarden, R. G. Newell, R. N. Robert, J. Econ. Literat. **55**, 1486–1525 (2017)

2. ETEKINA *H2020* Project, https://www.etekina.eu/

3. I. Bonilla, N. Nieto, L. del Portillo, B. Egilegor, H.Gastañaga, *ECEEE Industrial Efficiency*, Berlin *(*2018)

4. R. Franke, F. Casella, M. Sielemann, K. Proelß, M. Otter, M. Wetter, 7th International Modelica Conference, 122–130, Como, Italy (2009)