Mathematical Modeling of Combustion Chamber Using GS GFM Package

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Glass Service, Inc., has been developing own glass furnace simulation CFD package for the last 13 years. An important part of the package is combustion solver, called GS Combustor. The first part of this paper summarizes quantities that have to be calculated by the combustion solver and what dependencies exist among them. They include momentum, energy, radiation, turbulence, chemical species and pollutant transport equations, approximation of dissociation effects and mutual influence of glass and combustion space via heat transfer, volatilization and release of batch gases.

Another part of the paper identifies a common misinterpretation in combustion modeling: Users very often tend to estimate the flame shape from the temperature field, assuming that high-temperature areas are identical with visible flame areas. An example demonstrates how misleading the assumption can be. A better way of judging the shape of a visible flame is suggested.

The last part focuses on time-averaging in the furnace models. Many glass furnaces, namely the regenerative ones, do not operate in a steady state. Thus, a simple steady-state calculation is not sufficient. Methods of time averaging for such calculations are described. In some cases, such as regenerator simulations, no time averaging is applicable. However, a recent development has resulted in "regenerator coupling" method. That, combined with another simplification – porous wall approximation of the checkerwork geometry - has resulted in an easy and reasonably fast regenerator modelling procedure.

GS Combustor overview

GS Combustor is a part of GS Glass Furnace Model package. It is a CFD (Computational Flow Dynamics) combustion solver, based on finite volume method. The program reads files prepared by GS CAD and other GS Glass Furnace Model preprocessors. The output is also supposed to be processed and visualized by GS postprocessors.

Features

- Non-premixed, partially and fully premixed turbulent combustion
- Works on non-uniform orthogonal grids
- Gray radiation model (DOM, SLWSGG)
- Single-step or two-step chemistry model (Arrhenius + Eddy Dissipation rates)
- Liquid discrete phase for oil fuels
- k-e turbulence model
- Pollutant formation models (NOx, soot, NaOH)
- Automatic coupling with Glass model, including batch gases

Applications

GS Combustor has been successfully used to simulate regenerative furnaces (end-fired, cross-fired, side port, under port), recuperative furnaces, oxygen furnaces, furnaces with oxy boosting and/or air enrichment, furnaces with staging (including OEAS), working ends (including cooling air), forehearts (including cooling air), regenerators, atmospheres in cold-top melters, atmospheres above tin bath (including heating elements), batch preheaters and atmospheres around LCD overflows.

Complexity of the system

Figure 1 shows mutual influences of physical variables in the main combustion solver. Note that it does not include physical relationships in solid regions and porous walls and also interactions between the combustion space and glass melt. Also, it does not include all dependencies that exist in general transport equation, i.e., that transport of all physical variables depends on fluid density, velocity and turbulent viscosity.

Judging the flame shape

When interpreting results of combustion modeling, a very important output is often the flame shape. It is useful, e.g., to judge whether the flame hits the refractories and where is the combustion heat radiated to glass surface.

It is important to realize that human eye does not see directly temperature field – what we see is emission of radiation in visible bands. However, the gases in glass furnaces radiate mainly in infrared bands. The flame visibility is then determined mainly by presence of soot particles, which radiate also at visible wavelengths.

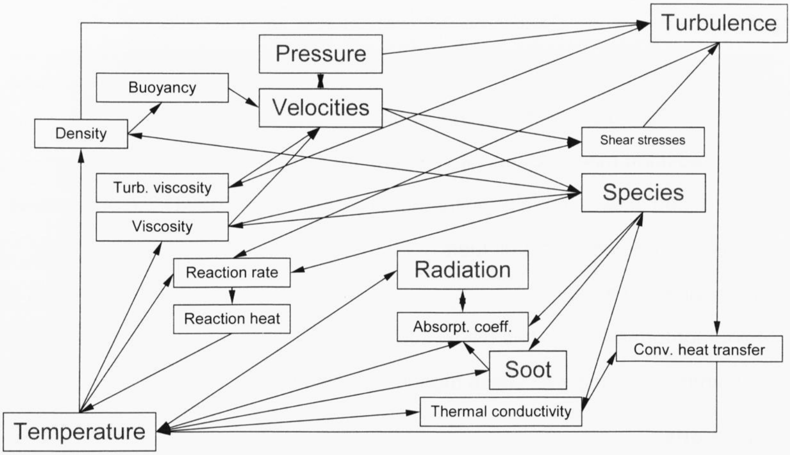

Figure 1. Interactions of variables in combustion model

Many users assume that the flame shape is identical with the temperature field, i.e., that high local temperatures imply presence of flame. This assumption is wrong. For example, flames in many recuperative furnaces are not visible at all.

Another well-accepted method of judging the flame is concentration of intermediate species, such as CO. The idea is that presence of CO indicates that the fluid is still reacting. This assumption is good unless the flame is fuel-rich. In fuel-rich flames, a part of carbon monoxide is always left unburnt, which obviously does not mean that the flame is infinitely long. This method is also useless for comparison of flames with different combustion ratios or for two-stage combustion systems.

A similar method is watching production of heat from combustion. This method is better than CO because it shows exactly where combustion takes place. But it still cannot tell us whether the flame is visible and where is the heat being radiated out.

From the above, we may conclude that we need to work with soot concentration field. But the soot concentration itself is not a good indicator because presence of soot still does not have to mean that there is a heat available to be radiated.

In Combustor, a total (effective) absorption coefficient a is calculated. It takes into account both absorption of gas and soot. We can then calculate blackbody function to get total heat radiated out of the flame:

$$Q_{flame} = 4a\sigma T^4$$

We call this quantity *flame luminosity*. Figure 2 and Figure 3 compare the variables we discussed as candidates for the flame shape evaluation.

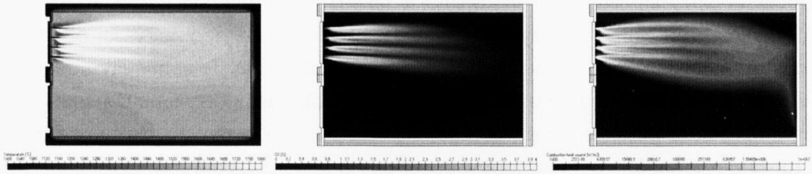

Figure 2. Temperature [°C], CO [kg/kg] and heat from combustion [W/m^3] fields

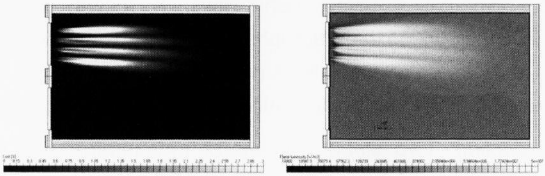

Figure 3. Soot [kg/kg] and flame luminosity [W/m^3] fields

Time averaging

Modeling studies, which compare two or more cases, are usually based on different steady states of different furnace designs/setups. In reality, of course, there are transient processes in the furnace even during steady conditions. Air preheating by regenerators is a typical example: Temperature distribution in the combustion chamber changes with every reversal and so does the heat flux to the glass melt. Thus, we have to find a time-averaged representative of the heat flux between glass and combustion space. A common method is symmetrization of the heat fluxes.

Some regenerative furnaces are, however, not symmetrical – for example, in end-fired container furnaces, the doghouse and batch chargers are often on one side only. As the batch melts, relatively cold gases (100 to 1000°C) are released, having a strong cooling effect on the crown. This makes the combustion space strongly unsymmetrical. In such cases, we calculate two combustion models (one for firing on left, one for firing on right) and the radiative intensity, passed to the glass model, is an average of radiative intensities from both models.

Modeling regenerators

GS Combustor can be used also for regenerator modeling. However, there are several new difficulties: There is neither steady state nor a reasonable time-averaged state. If we employ transient calculation, we need to start from a physically meaningful state. The most reliable method is to simulate regenerator heat-up. When we approach normal process temperatures, we have to start simulating the reversal process. Just like in reality, it takes many reversal cycles to get to a periodical (or "quasi-steady") state. The checkerwork geometry is often very complicated, requiring a fine grid. It is also difficult to satisfy continuity equation in such geometries. Due to the difficulties, the computation is very time-consuming and it is difficult to obtain a converged solution. In practice, it is possible to use the full transient model for regenerators with simpler geometry of the regenerator packing, e.g., if the blocks form separated ducts (chimney block packing). However, even in such models, computation takes many days. A recent development in GS Combustor, described in next paragraphs, provides the users with two possible simplifications in regenerator simulations (see below). Combination of them reduces CPU time, needed for regenerator simulations, from weeks to hours.

Regenerator coupling: Two steady models of regenerator (one simulating firing mode, another one for exhaust mode) are coupled via heat inertia of the solid regions. The checker temperatures eventually converge to a quasi-equilibrium state.

Porous wall approximation: The complex geometry of the checkerwork can be approximated by a porous wall model – a special zone where empirical equations are used for heat transfer and inertia loss calculations. The grid then does not have to cover the complex checkerwork geometry anymore so it leads to dramatic decrease of grid complexity.

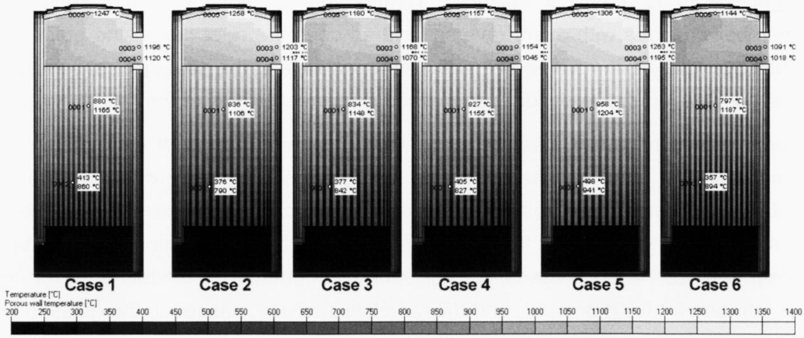

Figure 4. Example cases of regenerator modeling: **1.** A base case, **2.** 70% air and flue gases, **3.** 120% air and flue gases, **4.** 140% air and flue gases, **5.** 80% air, 100% flue gases (staging simulation), **6.** Dry air (less radiative heat transfer)

Conclusions

GS Combustor is a powerful and user-friendly combustion solver. Automatic coupling with GS glass model ensures tight interaction between the models via radiation, convection, volatilization and batch gas production. Even if model of combustion chamber is not of interest, it is useful to calculate coupled model to ensure that teh glass model has accurate boundary conditions on the glass surface.

The flame luminosity seems to be the best method of flame shape visualization. This quantity is usually different from the temperature field. Assumption that flame shape corresponds with temperature is wrong and is not recommended.

A recent development of the *regenerator coupling* method and the porous *wall model* has simplified simulation of regenerators, reduced calculation time from weeks to a day and made simulation of industrial regenerators easily realizable.

References

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