ITM Oxygen development is a multi-phase program. The overall goal of Phase I is to develop the ITM Oxygen technology to the point of demonstrating all necessary technical and economic requirements for further scale-up to the 5-TPD production scale. Phase II activities will focus on construction and testing of a 1-TPD unit, followed by further scale-up to 5 TPD oxygen production. The Phase II project will provide the design, engineering, cost, and scale-up data for a Phase III, 25- to 50-TPD, pre-commercial demonstration unit, fully integrated with a gas turbine and tested at a suitable field site. By the end of Phase III, sufficient demonstration of all essential aspects of the technology will have occurred to enable further industrial commercialization in the 2005 to 2007 time frame.

Disclaimer

Conclusion

Air Products has introduced unique cryogenic ASU designs for integrated and non-integrated operation with gas turbines at a number of gasification facilities worldwide. The introduction of higher pressure ratio gas turbine equipment offers the opportunity to explore new ways to integrate ASU and gas turbine operation for further improvement in project economics. Gas conversion projects have differing technical and economic criteria from IGCC facilities, including the potential need for shipboard operation. Future developments in ASU design, integration and operation will continue to increase single train sizes and reduce the capital and operating costs of gasification projects. The new ITM Oxygen process uses mixed-conducting, ceramic membranes to produce high-purity oxygen at a high flux rate from a hot, compressed air stream. By integrating the energy-rich, vitiated, non-permeate stream with a gas turbine system, the ITM Oxygen process becomes a highly efficient co-producer of oxygen, power, and steam.

The Flow of Liquid Coal-Ash Slag down the Refractory Wall of a Gasifier

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Abstract

In this paper a model is described and used to calculate the radiative heat transfer and the liquid coal-ash slag flow in a gasification reactor. Because the heat transfer and slag flow are interacting, a description that couples these two is used. Special attention is given to the outflow cone. Different parameters are varied e.g. slag deposition, burner temperature and viscosity. The most important of these turns out to be the viscosity as a function of the temperature.

Introduction

In modern integrated gasification combined cycle (IGCC) plants, like in Buggenum in The Netherlands, it is common to use entrained flow gasifiers. In the gasifier coal is being converted into gas, fly ash and coal-ash slag on the gasifier wall. It is possible to design the reactor in such a way, that the slag is being used to protect the wall of the reactor. The geometry of such a reactor is presented in Figure 1. It is required that the wall of the reactor is covered with slag everywhere and that the slag flows continuously. This flow will be modeled in this article.

Physical Model

The physical background of the model is described in this section. The equations that describe the slag flow, the gas temperature profile in the reactor and the radiative heat transprort to the wall.

The model is based on a local equilibrium of heat transport and slag flow. By integration of the local solution with fixed total heat output, the temperature and slag flow in the reactor is obtained.

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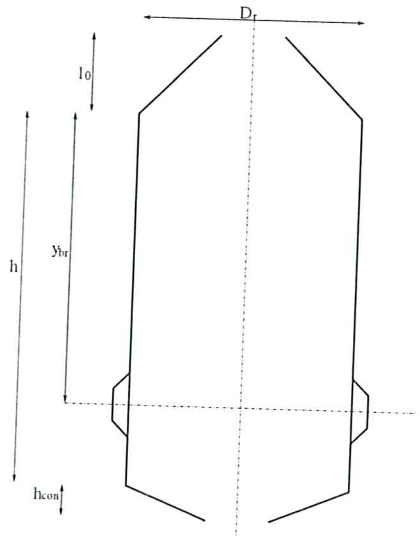

Figure 1: Gasification reactor

Local equilibrium of heat and slag flow

The transport of heat and the flow of the coal-ash slag are interacting. The flow of the slag determines the thickness of the slag layer and therefore the heat resistance of the slag layer. The viscosity of the liquid coal-ash slag varies strongly with the temperature. This makes the slag flow dependent on the heat transport.

Under equilibrium conditions, if all heat is transferred by radiation and if the reactor is isothermal and is everywhere covered with slag, we can use the double identity for the heat flux q'' [1]:

$$q'' = \frac{T_s - T_o}{R_{sl} + R_w} = \epsilon\sigma(T_{gas}^4 - T_s^4), \tag{1}$$

where T_s is the surface temperature of the slag layer, T_o is the temperature of the cooling pipes in the refractory wall, T_{gas} is the gas temperature in the reactor, R_{sl} and R_w are respectively the heat resistances of the slag layer and the refractory wall, ϵ is the emission coefficient and σ is the Stefan-Boltzmann constant. According to [2] and [5] the emission coefficient can be taken $\epsilon = 0.9$.

The laminar, viscous flow of the slag can be described by:

$$\tau_{xy} = \mu(T)\frac{\partial v}{\partial x} = \rho g(\delta(y) - x), \tag{2}$$

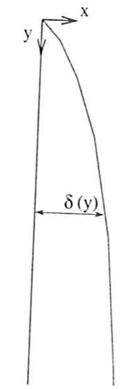

Figure 2: Slag flow on reactor wall

where τ_{xy} is the shear stress exerted in y-direction, $\mu(T)$ the viscosity depending on the temperature T, v the velocity in vertical direction, x the horizontal coordinate, ρ the density of the slag, g the acceleration due to gravity and $\delta(y)$ the thickness of the liquid slag layer as a function of the vertical coordinate y, see Figure 2.

For the integration of eq. (2), the following conditions are required:

$$v = 0 \qquad \text{at} \quad x = 0, \tag{3}$$

which is the no-slip boundary condition at the wall. The volume of coal-ash slag flow per unit of circumference of the wall that flows out of the reactor $\Gamma(y)$ is given and should be equal to:

$$\Gamma(y) = \int_0^\delta v dx. \tag{4}$$

The distribution of the volume flow $\Gamma(y)$ has been varied. Calculations have been performed both with a homogeneous distribution of coal ash slag and a non-homogeneous distribution. Both based on the given amount of slag of $2kg/s$ that flows out of the reactor.

Note that the eqs. (2) - (4) also describe the flow in the cone. For that situation the acceleration of gravity is replaced by the component along the cone.

The equations described above are used to calculate the local heat transfer and slag flow at discrete y-positions in the reactor.

Axial gas temperature profile reactor

The heat release from the reactor is known. The temperature profile in the reactor is obtained by integration of the local heat flux on the refractory wall keeping the total heat release fixed.

By having a closer look at the processes in the reactor, we see that:

- At the bottom of the reactor exothermal reactions take place, where a lot of heat is being released. Gases heat up here.
- In the upper part of the reactor no heat is being produced and the gases cool down.

To describe this behaviour, it is convenient to divide the reactor into two parts. In the upper part (area 1) plug flow with heat transfer in radial direction has been assumed. The cooling of the gas in this case is given by:

$$q''(y) = \frac{1}{4}\rho_g C_p D_r \overline{U}_g \frac{\partial T_{gas}(y)}{\partial y} \qquad 0 < y < y_{12}, \tag{5}$$

where ρ_g is the density of the gas, D_r is the diameter of the reactor, $\overline{U}_g$ is the mean gas velocity and y_{12} the transition point between area 1 and area 2. T_{out} has to be specified.

In the lower part of the reactor (area 2), including the cone, a temperature profile is assumed:

$$T_{gas} = c_1(y - y_{br})^4 - c_2(y - y_{br})^2 + T_{br} \qquad y_{12} < y < y_{br}, \tag{6}$$

$$T_{gas} = T_{br} - c_3(y - y_{br})^2 \qquad y > y_{br}, \tag{7}$$

where T_{br} is the burner temperature, y_{br} is the vertical burner position, c_1, c_2, and c_3 are constants that have to be determined. c_1 and c_2 follow from the requirement that the temperature profile between area 1 and 2 should be smooth. c_3 follows from the temperature at the slag tap T_{con}. T_{con} and T_{out} have to be specified. A typical temperature profile is shown in Figure 3.

The temperature profile is described by eqs. (5) - (7). In the model these equations are coupled with the slagflow eq. (2), using eq. (1). The system of equations has been discretised and numerically solved.

The next two paragraphs to focus on depostion of the coal-ash slag on the refractory wall and on the viscosity of the coal ash-slag.

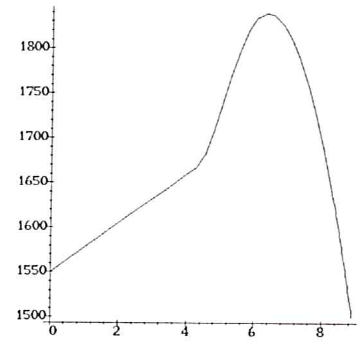

Figure 3: Typical gas temperature profile for vertical reactor wall.

Coal-ash Slag Properties

In the analysis of coal-ash slag, two parameters are important: the kinematic viscosity as a function of the temperature $\nu(T)$ and the so-called critical temperature. At high temperatures, the slag behaves as a free-flowing Newtonian liquid. When the temperature decreases under a certain temperature, called the critical temperature T_{cv}, the flow of slag gets a plastic behaviour, see [3]. In this research , it is assumed that if the slag temperature decreases under T_{cv}, the slag coagulates. In other words, T_{cv} is treated as the melting temperature of the coal-ash slag.

In our calculations, we use 3 different types of coal, namely Drayton69, El Cerrejon (BIN 10886) and Drayton (BIN 10957). Drayton69 is used for most calculations, while the other two are used to investigate the influence of slag viscosity. For Drayton69 we use the following relation for the viscosity as a function of the temperature:

$$\log \mu = a + b \log T + \frac{c}{T} \qquad T < T_{cv}, \tag{8}$$

where T is the temperature. The parameters a, b and c yield for Drayton69: $a = -149.9$, $b = 39.8$ and $c = 41400$. The critical temperature $T_{cv} = 1150°C$.

For El Cerrejon and Drayton we use:

$$\log \mu = B - A(T - T_1) \qquad T < T_{cv}, \tag{9}$$

where A, B and T_1 are slag dependent parameters, see Table 1.

	A	B	$T_1(°C)$	$T_{cv}(°C)$
El Cerrejon	$6.18 \cdot 10^{-3}$	3.31	1283	1300
Drayton	$4.49 \cdot 10^{-3}$	3	1055	1100

Table 1: Characteristic parameters for El Cerrejon and Drayton.

h	$8.3m$	HP	$20MW$
D_r	$3.8m$	C_p	$1800J/kgK$
α	$23°$	ρ_g	$3.7kg/m^3$
y_{12}	$4.3m$	$\overline{U}_g$	$1m/s$
y_{br}	$6.3m$	g	$9.8m/s^2$
T_{con}	$1500°C$		

Table 2: List of constants used.

Results

In this section the results of the calculations are presented. The section is divided into to paragraphs: the vertical wall and the slag outflow cone. The reason for this is that for the cone some specific properties are investigated, that have nothing to do with the vertical wall. We note that all calculations are performed for the complete reactor.

Vertical Wall

In the calculations in this section several parameters are varied: slag deposit function v_{sl}, gas outflow temperature T_{out}, cooling-water temperature T_o and the viscosity $\nu(T)$. The parameters that are set to a constant value in this calculations are presented in Table 2.

Results of seven runs are presented here. The parameters that are varied are shown in Table 3. For several runs, run no. 2 is used as a reference case.

From our calculations we observe that lowering the outlet temperature leads to a higher burner temperature. Lowering the outlet temperature by about $100°C$ leads to burner temperatures that increase by $175°C$. This can lead to dangerous high burner temperatures. If the temperature around the burner raises over $2000°C$, the thickness of the solid slag layer decreases to less than $0.5\,mm$, which can damage the refractory wall. A change in the cooling-water temperature has only little influence on the thickness of the liquid slag layer. Flow behaviour and heat distribution in the reactor are

Run no.	deposit	coal	$T_{out}(°C)$	$T_o(°C)$
1	non-hom.	Drayton69	1550	250
2	non-hom.	Drayton69	1500	250
3	non-hom.	Drayton69	1450	250
5	non-hom.	Drayton69	1500	350
7	hom.	Drayton69	1500	250
8	non-hom.	El Cerrejon	1550	250
9	non-hom.	Drayton	1550	250

Table 3: Performed runs.

not influenced.

It is surprising that the slag deposition distribution (homogeneous/non-homogeneous) has little influence on the flow behaviour and the heat transport. It is believed that for practical situations, where the behaviour is not stationary, but dynamical, this is not correct. Our model does not describe these effects.

The most important parameter turns out to be the viscosity behaviour of the coal-ash slag. In particular the temperature of critical viscosity T_{cv}. For lower T_{cv}, a thick, isolating, slag layer is being formed in the top of the reactor. This causes less heat transport in this part of the reactor and more heat transport in the bottom half. This last effect causes a higher temperature at the burner. An other important parameter is the steepness of the viscosity curve. El Cerrejon that has a high T_{cv} also has a steep viscosity curve. This causes a lower temperature gradient in the slag layer and therefor compensates somewhat for the high T_{cv}.

It follows from all calculations that the variation in liquid slag layer thickness is small compared to the variation of the thickness of the solid slag layer. Nevertheless the thickness of the liquid slag layer plays an essential role in the heat transport in the reactor.

Cone

In this section the results are presented from calculations where the temperature at the slag tap T_{con} and the slag tap angle α have been varied. The several runs are described in Table 4.

In the cone calculations the burner temperature is set to $T_{br} = 1954°C$, which followed from run no.2 from the previous section. Together with T_{br}, T_{con} determines the gas temperature in the cone. It is assumed that adjusting parameters in the cone has little influence on the total flow and

Run no.	coal	$T_{con}(°C)$	α
10	Drayton69	1500	23
11	Drayton69	1400	23
12	Drayton69	1300	23
13	El Cerrejon	1500	23
14	Drayton	1500	23
15	Drayton69	1500	30
16	Drayton69	1500	17.5
17	Drayton69	1500	5

Table 4: Performed runs.

heat transfer in the rest of the reactor. This is our motive for using a fixed burner temperature. The advantages of a fixed burner temperature are that it saves calculation time and that it makes comparing of the different runs for the cone easier.

One of the most important consequences of the slag ash tap is the increase in velocity of the coal-ash slag flow. The influence of the gravitational acceleration on the thickness of the slag layer is not so large. This is due to the fact that the thickness of the slag layer δ is proportional to $g^{1/3}$, see [4].

$$\delta = \left\{ \frac{3\Gamma\mu}{\rho g} \right\}^{\frac{1}{3}}, \tag{10}$$

The influence of the viscosity is again an important factor. A low gas temperature at the slag tap causes a lot of slag to build up at the tap. Up to $76\,mm$ for a temperature $T_{con} = 1300°C$. The influence of the slag tap angle α is studied at the end of the slag tap. Because the strong variation of α, the length of the cone varies a lot and therefore of the results in the rest of the cone are difficult to compare. Although the variation of α is large, $5 - 30°$, the effect on the slag layer thickness and the velocity profile is limited. The effective acceleration due to gravity is $g \sin\alpha$. By using 10, we find that the maximal ratio between two layers is:

$$\frac{\delta_5}{\delta_{30}} = \left\{ \frac{\sin 30}{\sin 5} \right\}^{\frac{1}{3}} = 1.8. \tag{11}$$

This explains the little influence of the variation of the slag tap angle.

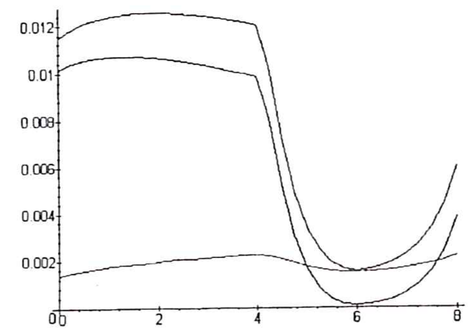

Figure 4: Thickness (liquid, solid, total) of slag layer along the wall, run 3 .

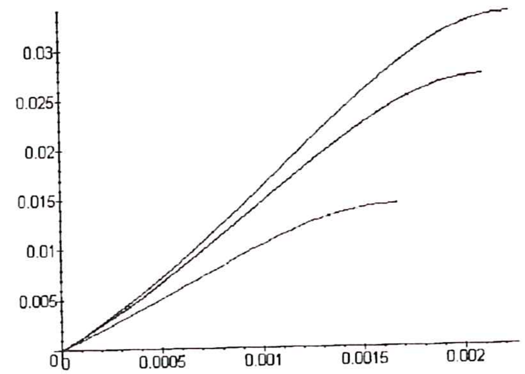

Figure 5: Velocity profiles across several cross sections, run 3.

Discussion and future work

The calculations presented in this research indicate that the viscosity as a function of the temperature is an crucial factor for the flow of coal-ash slag down the refractory wall. Another important parameter is the outflow temperature of the gas. Both the cooling-water temperature and the deposition distribution influence the heat transport and the slag flow in the reactor hardly. However this last observation may not be realistic. A non-stationary model, which is not only based on our relatively simple equilibrium of heat transport and slag flow, will be influenced by different deposition functions. The development of such a model will lead to a model that is able to predict start- and shutdown behaviour.

An important consequence of the slag tap is that the slag velocity increases considerably. The influence of the slag tap angle is limited. This is explained by described non-linear relationship between layer thickness and the gravitational acceleration.

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3.4 Research on gasification aspects