Increasing the heat transfer from oxy-fuel flames to glass products is a major issue in the lighting industry. We show that oxy-fuel flames differ a lot from air-fuel flames in the sense that there are still a lot of radicals in the burnt gas mixture, which contain a lot of energy. Furthermore, we have calculated the heating of a thin glass plate, using a one-dimensional model based on the instationary conduction equation. This model shows that the strain rate of the flame is an important parameter in the heating process. We conclude by showing that the burnt mixture near the plate is not in chemical equilibrium. Therefore surface chemistry possibly contributes in the heating process and it was studied theoretically by assuming a platinum surface on the quartz plate. As a result the heat production increases significantly.

1 Introduction

Mixtures of oxygen and a fuel gas are frequently applied in various industrial processes. Flame applications for cutting processes use an oxy-fuel flame and straight oxygen as a cutting jet to separate the metal, while flame welding is performed with a welding torch and an oxy-acetylene or oxy-crylen flame. Also, the high velocity oxy-fuel coating process can be used with various fuel gases such as hydrogen, acetylene, LPG’s or kerosene, depending on the powder properties [1]. In the early nineties, large-scale glass manufacturers adopted the oxy-combustion technology as well [2], while the lighting industry, however, has been using premixed oxy-fuel combustion since the late sixties, early seventies. The need for high heat transfer rates leading to short processing times was the most important reason for the lighting industry for the move to gas-oxy firing. High heat transfer rates are needed when the energy consumption of the process is relatively high, while short processing times are needed for reasons of product quality. Furthermore, oxy-fuel melting represents the most optimal method to meet the environmental regulations (reduction of NOx emissions) and to achieve substantial process improvements without increasing overall costs, comparing to other options like electric melting and air preheating [3].

Rapid heating of products is a common process in the lighting industry and for this purpose high velocity burners are used. A considerable amount is known about these burners, while on the other hand other investigations are focused on glass properties. These investigations are mainly performed for applications using glass furnaces, where the processing time of the products is longer and degassing processes, which greatly affect the glass properties, are essential for obtaining a high-quality glass product [4]. However, as mentioned before, short processing times are needed for reasons of product quality for the melting of glass components in the lighting industry. For this application there is a need for knowledge on heat transfer from flames to glass products and that knowledge is very limited.

To gain more scientific knowledge of the heat transfer of an oxy-fuel flame to glass products, several phenomena need to be identified, modeled and quantified. The first phenomenon is flame chemistry, because
the burnt gas mixture still contains, apart from thermal energy, chemical energy which can be converted to heat. Secondly, the flow characteristics play an important role because turbulence, if having a sufficiently large intensity, can enter the boundary layer on the glass product and significantly alter the heat transfer. The formation of boundary layers on glass is important to understand, while the steeper the temperature gradients near the glass product, the larger the heat transfer. Furthermore, the radiative heat transfer from the flame to the glass and radiative losses from the glass to the surroundings need to be studied. Finally, surface and volume chemistry cause chemical reactions which either consume or produce heat.

In this paper, the role of conductive heat transfer from the flame to the glass product and the role of surface chemistry are treated. In the next section the main differences between free oxygen fuel flames and free air fuel flames are discussed first. Then the heat transfer by conduction from the flame to the plate is studied. It seems that the so-called strain rate of the oxy-fuel flame affects the heat transfer to the glass product significantly. The third section treats the effect of the strain rate in more detail. Finally, since the burnt gases near the product are not in chemical equilibrium, surface chemistry may influence the heat transfer. This is explored in the last section. The models that will be discussed are all one-dimensional, although the system under study is in principle two-dimensional (see Fig. 1).

2 Free oxy-fuel and air-fuel flames

Adiabatic free flames are simulated with the numerical code CHEM1D [5]. Only stoichiometric flames at atmospheric pressures are considered and computations are performed for methane-air, hydrogen-air, methane-oxygen and hydrogen-oxygen mixtures. It is assumed that the air consists of oxygen and nitrogen only, where the mole fraction of oxygen is 0.21. A Mari- nov reaction mechanism [6] is used for the hydrogen-oxygen and hydrogen-air flames. This scheme includes 10 species and 29 reactions. The reacting species consist of the elements hydrogen and oxygen only. Nitro- gen is considered inert and participates only in the chemistry by third body reactions. The GRI3.0 reaction scheme [7] is used for the methane-oxygen and methane-air flames. This scheme consists of 53 species and 325 reactions including nitrogen reactions. Complex transport models [8] were used to include diffusion processes. Gas enters the domain at \( x = -2.0 \) cm with a temperature of 300 K. At approximately \( x = 0 \) cm the main reactions start, which results in a temperature increase. Table 1 shows the burning velocities and flame temperatures. The laminar burning velocity of hydrogen-oxygen mixtures is about three times the burning velocity of methane-oxygen mix- tures. It seems that the chemical equilibrium of hydrogen-oxygen and methane-oxygen mixtures is such that the flame temperatures of hydrogen-oxygen and methane-oxygen flames are comparable.

Figure 2 shows the temperature profiles of a free adiabatic hydrogen-oxygen and hydrogen-air flame. Within a few millime-

<table>
<thead>
<tr>
<th>( \chi )</th>
<th>( v_L ) ([\text{cm/s}])</th>
<th>( T ) [K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH(_4)-air</td>
<td>36.9</td>
<td>2229</td>
</tr>
<tr>
<td>H(_2)-air</td>
<td>239.8</td>
<td>2387</td>
</tr>
<tr>
<td>CH(_4)-O(_2)</td>
<td>311.3</td>
<td>3075</td>
</tr>
<tr>
<td>H(_2)-O(_2)</td>
<td>1026.1</td>
<td>3079</td>
</tr>
</tbody>
</table>
Figure 2: Flame temperatures as function of position for an adiabatic hydrogen-oxygen flame (solid line) and hydrogen-air flame (dashed line).

Figure 3: Species mole fractions of the main species as a function of position for a hydrogen-oxygen flame.

Figure 4: Species mole fractions of radicals as a function of position for a hydrogen-oxygen flame.

Figure 5: Species mole fractions of the main species as a function of position for a hydrogen-air flame.

Figure 6: Species mole fractions of radicals as a function of position for a hydrogen-air flame.

The burnt gas is at its adiabatic temperature and the system is in equilibrium. The flame temperature for a hydrogen-oxygen flame is much higher than the flame temperature for a hydrogen-air flame. Figures 3 and 4 show the species mole fractions of the main species and radicals in the hydrogen-oxygen flame. The burnt mixture is rapidly in equilibrium. Although most of the hydrogen and oxygen reacts into water, there is still a lot of $\text{H}_2$, $\text{O}_2$ and radicals in the burnt mixture, much more than in the case of a hydrogen-air flame, as can be seen from figures 5 and 6. A similar conclusion can be drawn for the differences between methane-oxygen and methane-air flames.

3 Heat transfer

As a first step we consider the heating process of a flat glass plate of thickness $L$, by looking at the flame-plate interaction in a simple way. The reacting gas is considered as a hot inert gas flowing in the form of a plug flow towards the plate (see fig-
ure 1 for the real situation). A stagnation flow develops close to the plate. The one-
dimensional instationary conduction equation for the glass to be solved is given by:
\[
\frac{1}{\alpha} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2},
\]
(1)
where \(\alpha = \lambda/\rho c\) is the thermal diffusivity of the conducting material \([m^2/s]\), with \(\lambda\) the thermal conductivity coefficient \([W/(m \cdot K)]\), \(\rho\) the density \([kg/m^3]\) and \(c\) the specific heat \([J/(kg \cdot K)]\).

The solution of equation (1) can be obtained using the method of separation of variables, i.e.
\[
T(x, t) = (C \cos(kx) + D \sin(kx))e^{-k^2\alpha t},
\]
(2)
in which the value of \(k\) and the constants \(C\) and \(D\) can be determined using boundary and starting conditions. The initial temperature \(T(x, 0)\) is taken to be homogeneous 300 K, and we assume that the top side of the plate exchanges no heat with the surroundings in order to be able to obtain the solution analytically, so \(\lambda(\partial T/\partial x)|_{x=L} = 0\).

The boundary condition at the bottom side \((x = 0)\), where the gas hits the plate, will be determined using the relation for the stagnant boundary layer. The heat flux from the flame must be equal to the heat flux entering the quartz plate, so
\[
\lambda_g \frac{\partial T}{\partial x}|_{x=0} = \lambda_q \frac{\partial T}{\partial x}|_{x=0},
\]
(3)
with \(\lambda_g\) the conduction coefficient of the gas and \(\lambda_q\) the conduction coefficient of the quartz plate.

The solution for the stagnant boundary layer can be found if we assume that the flame is inert and the boundary layer itself adjusts instantaneously. In that case, the conservation equation for the gas is a balance between convection and conduction:
\[
\rho u c_p \left( \frac{\partial T}{\partial x} \right) = \left( \frac{\partial}{\partial x} \left( \lambda_g \frac{\partial T}{\partial x} \right) \right).
\]
(4)

Strain is a very important parameter of the flame, while it is an indicator of how much the gas velocity decreases when it approaches the plate. In other words, a higher strain rate means that the flame pushes harder against the plate, so the boundary layer becomes thinner \((\partial T/\partial x)\) is higher) and the heat flux which enters the plate is higher. Now, assuming that the mass flow near the plate decreases linearly, so \(\rho u = -K \rho x\), with \(K\) the strain of the gas \([1/s]\), the boundary condition at the bottom side of the plate can be found using (3) and (4):
\[
\frac{\partial T}{\partial x}|_{x=0} = (T(0) - T_{\text{flame}}) \frac{\lambda_g}{\lambda_q} \left( \frac{2K}{\pi} \right) \exp[-k^2\alpha t].
\]
(5)
with \(\kappa = \rho c_p K / \lambda_q \) \([1/m^2]\).

With the initial condition and the boundary conditions, equation (2) can be solved. The general solution is a result of superposition of all the linear solutions:
\[
T(x, t) = T_{\text{flame}} - \sum_{n=1}^{\infty} C_n \cos(k_n(L - x)) \cdot \exp[-k_n^2\alpha t].
\]
(6)
This can be recognized as the Fourier half-range cosine series. Furthermore, \(C_n\), the Fourier coefficient, and \(k_n\), the eigenvalues, are given by:
\[
C_n = \frac{2T_{\text{flame}} \sin(k_nL)}{\sin(k_nL) \cos(k_nL) + k_nL},
\]
(7)
\[
k_n = \frac{n\pi}{2L} \left( 1 - \frac{1}{\mu L} \right). \quad \text{for } n = 1, 3, 5 \ldots
\]
(8)

Figure 7 shows the temperature distribution after 0, 2, 4, 6, 8 and 10 seconds for a strain rate of the flame of \(K = 2000 \) 1/s. As mentioned before, the strain rate of the flame is an important parameter in the heating of the glass products. The difficulty however is to assign a value for this parameter.

An experimental set-up was built to validate the results obtained with the analytical model. We measured the temperature increase at the top side of the plate using a thermocouple while the plate was heated by an oxy-fuel flame. Figure 8 shows the results of the experiment (solid line) and the analytical solutions (dashed lines) for \(K = 2000 \) 1/s and \(K = 1000 \) 1/s, respectively. By choosing the proper value for the strain rate, the experimental results can properly be predicted.

During the experiments, there appeared to be no difference in the heating of the plate
Figure 7: Temperature profile of a quartz plate with a thickness of 5 mm after 0, 2, 4, 6, 8 and 10 seconds

Figure 8: Temperature increase of the top side of the plate while the bottom side is heated by an oxy-fuel flame. The solid line represents the experimental results, while the dashed lines represent the results of the analytical model for $K = 2000 \, 1/s$ (above) and $K = 1000 \, 1/s$ (below)

using different gas velocities, i.e. different strain rates, for both methane-oxygen and hydrogen-oxygen flames. This was rather contradictory to the results obtained with the analytical model, which clearly show the dependence on the strain rate. This can be explained by realizing that if during the experiment the gas velocity is increased, the flow will diverge and so the boundary layer will not become smaller. Plans for the near future are to execute velocity measurements of the flame while it is heating a plate, in order to measure the strain rate and to make a quantitative comparison with the analytical model possible.

4 Surface chemistry

Surface chemistry is studied at the surface of a quartz plate that is heated by a hydrogen-oxygen flame. For the hydrogen-oxygen flame a 16 species 25 reactions skeletal CH$_4$-air reaction mechanism is used [9]. Before analyzing the surface reactions, the gas composition near the surface is studied. Surface chemistry may play a role only if the gas near the surface is not in chemical equilibrium. A burnt mixture and a mixture in local equilibrium with the same thermal conditions are compared. The burnt mixture approaches from the left and impinges on the plate at $x = 0$. Initially the surface is considered inert. The plate is at a uniform temperature of 700 K initially. A convective boundary condition is used for the other side of the plate. The plate is heated in time by the burnt mixture. As a result both the plate and gas composition near the plate change in time.

In figures 9 and 10 the species profiles of H$_2$ and O$_2$ in a burnt mixture are plotted for several times (solid lines). For the same times also the chemical compositions are calculated when the gas would be in chemical equilibrium and with the thermal conditions equal to those of the burned mixtures. In the figures the dashed lines correspond to the concentration profiles for the mixtures in local equilibrium. Close to the plate the solid lines and dashed lines differ substantially for all times. In the flame the H$_2$ and O$_2$ concentrations are much higher than in the equilibrium state. Therefore the burnt mixture is considered to be not in equilibrium near the plate and surface chemistry may play a role. At about 1 mm from the plate the burnt mixture is approximately in equilibrium.

Species may undergo heterogeneous reactions and release or consume heat at the surface. The heat transfer to the plate at $x = 0$ may be affected. To study the effect of surface chemistry, the quartz plate is considered to have a platinum surface. A the-
5 Conclusion

Main differences between oxy-fuel flames and air-fuel flames have been discussed; the adiabatic flame temperature of oxy-fuel flames is only 700 K to 800 K higher than air-fuel flames due to the fact that the burnt gases of a hydrogen-oxygen flame still contain a lot of H₂, O₂ and radicals. With a one-dimensional analytical model it is possible to calculate the heating of a glass plate. The strain of the flame is an important parameter of the model, although it is hard to quantify this parameter. In the future, experiments will be performed to estimate the strain rate of oxy-fuel flames in order to have a better comparison with the analytical model. Finally, it was shown that the burnt gases close to the surface are not in chemical equilibrium. As a result, possible influences of surface chemistry were studied by theoretically assuming a platinum surface on the quartz plate. With use of a well-known surface kinetic model it was shown that the heat-up time decreases by approximately 10% due to surface reactions.

References


