Original Paper

Influence of oxy-firing on radiation transfer to the glass melt in an industrial furnace: Importance of spectral radiation model[1)]

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Coupled reactive fluid dynamics and radiation calculations are performed in air and oxy-fuel-fired industrial glass furnaces using two gas radiative property models. The first one is the weighted sum of gray gases model and the second one is the correlated-*k* method, which is a spectral model based on the cumulative distribution function of the absorption coefficient inside a narrow band. The first model, generally used in glass furnaces, is less time-consuming than the second one. However, discrepancies up to several tens of percent are found in the local heat flux on the glass surface between the two radiative models, especially in air combustion.

Einfluß der Sauerstoffbeheizung auf den Strahlungsübergang zur Glasschmelze: Bedeutung des spektralen Strahlungsmodells

Mit Hilfe zweier unterschiedlicher Gasstrahlungsmodelle werden gekoppelte Berechnungen zur reaktiven Strömungsdynamik und Strahlung für industrielle, luft- und sauerstoffbeheizte Glasschmelzwannen durchgeführt. Das eine Modell beruht auf einer Gewichtung von grauen Gasen, das andere, ein spektrales korreliertes *k*-Modell auf einer kumulierten Verteilungsfunktion für den Absorptionskoeffizienten in einem schmalen Wellenlängenband. Das erste, überwiegend für die Modellierung von Glasschmelzöfen eingesetzte Modell arbeitet schneller als das zweitgenannte. Der lokale Wärmestrom zur Glasbadoberfläche unterscheidet sich jedoch um mehrere zehn Prozent, je nach verwendetem Modell, besonders bei Verbrennung mit Luft.

1. Introduction

Gas radiation represents an important mode of heat transfer in glass furnaces. Its importance increases with temperature especially in oxy-fuel furnaces where maximum temperatures are higher than 2000 K. Consequently, an accurate calculation of radiative fluxes is essential to improve the furnace efficiency, to predict the wall temperature or to simulate pollutant formation. In many engineering applications, it is necessary to account for the spectral fine structure of gas radiative properties. In spite of their accuracy, line-by-line calculations are not used because of their computational costs. Some approximate models have been proposed. Statistical narrow-band (SNB) models have been used to compute radiative intensities along line of sight in different flame configurations by Faeth et al. [1 to 4], or to study radiative transfer in planar [5 to 8] or in axisymmetrical geometries [9 and 10]. But the SNB model approaches present some disadvantages: a) the radiative transfer equation must be used in terms of transmissivities. This fact limits the choice of the method of resolution of the radiative transfer equation. b) The Curtis-Godson approximation [11], used for nonisothermal and nonhomogeneous gas mixtures, is not easy to employ for the required large number of transfer directions (a few hundreds typically); practically other approximations such as the correlation function approximation of Zhang et al. [9] and Soufiani and Taine [10] are required; c) a radiative transfer calculation based on transmissivities is not suitable for the treatment of gas-scattering particle mixtures. Similarly, the spectral correlation phenomena which appear in the reflected flux at a wall are not easily accounted for.

Another spectrally correlated approximate model, which does not present the previous disadvantages, is the cumulated *k* distribution function approach, called CK. It has been studied for atmospheric applications by Goody and Yung [12] and typically for combustion applications by Rivière et al. [13 and 14]. This method appears to be generally convenient for heat transfer purposes, except in the case of hot gas radiation transmitted through a long cold path of the same cold gas [13] which is not encountered in glass furnaces.

However, the radiation models that are mostly used for industrial configurations are based on the weighted sum of gray gases (WSGG) or even simple gray gas concepts [15 to 18]. The WSGG model has been first introduced by Hottel and Sarofim [15] in association with the zonal method. Modest [19] has shown that with the WSGG model and *N* gray gases the radiative transfer problem reduces to *N* radiative transfer equations if the absorption spectrum can be considered as spatially in-

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variant. He compared WSGG against spectral calculations for a hypothetical medium with an absorption coefficient uniform throughout the entire medium. Denison and Webb [20 and 21] have developed more elaborate versions of the WSGG model, based on the absorption line black body distribution function and tested it against line-by-line approach for water vapor in planar media. Song [22] has compared WSGG with wide-band results for planar geometries and Soufiani and Djavdan [23] have compared WSGG and SNB results in the case of planar and axisymmetric combustion systems. El Ammouri et al. [24] have made calculations in air and oxy-fuel-fired experimental furnaces using WSGG and CK models. They showed discrepancies between the two models, especially in air combustion.

In the present paper, the authors made coupled reactive turbulent fluid dynamics and radiation calculations in industrial air and oxy-fuel-fired glass furnaces using two gas radiative property models: the WSGG model with parameters by Taylor and Foster [25] and the CK spectral model with parameters by Rivière et al. [14]. Section 2. is related to a brief description of the radiative, turbulence and combustion models used to perform calculations. Comparisons between the results of the WSGG and CK models are discussed in section 3.

2. Analysis

The turbulent reactive flow within the furnace is simulated by solving the governing balance equations in their steady-state time-averaged form (see for instance Carvalho and Nogueira [17]).

Turbulence modeling is carried out by the classical (k, ε) model of Jones et al. [26]. Since the attention is focused on the prediction of radiative transfers, the elementary turbulent combustion model is used in order to provide realistic mole fraction fields in burnt gases. The combustion is described by the mixing rate controlling model proposed by Magnussen and Hjertager [27]. The only reaction considered here for oxy-methane combustion is:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O\,. \quad (1)$$

However, for the specific heats of the combustion products, the presence at equilibrium of species such as CO, H_2, OH, etc. is taken into account. The computational code ATHENA^{TM}, developed at Air Liquide, is used for the resolution of the governing equations. The numerical treatment of these equations is based on a classical finite-volume SIMPLE resolution method [28].

The radiative transfer equation is solved by using the discrete transfer radiation model described by Lockwood and Shah [18]. Two gas radiative property models are compared. The first one is the WSGG model and the second the CK model.

In the CK model, the spectrum inside a band of width $\Delta\nu$ is replaced by the reciprocal function $k(g)$ of the cumulative distribution function $g(k)$ of the absorption coefficient K_ν. For instance, the transmissivity of a uniform column averaged over $\Delta\nu$ is given by

$$\overline{\tau_\nu^{\Delta\nu}} = \frac{1}{\Delta\nu}\int_{\Delta\nu} \exp(-K_\nu l)\,\mathrm{d}\nu = \int_0^1 \exp(-k(g)\,l)\,\mathrm{d}g\,. \quad (2)$$

Unlike K_ν, the function $k(g)$ has no fine structure and the last spectral integration can be carried out using a few points of Gauss quadrature (seven points in this study). If the spectral absorption coefficient is a scaling function of the wave number [12], the intensity averaged over $\Delta\nu$ is for nonuniform media:

$$\overline{I_\nu^{\Delta\nu}} = \sum_{n=1}^{7} \omega_n I_{\nu n}(s) \quad (3)$$

where the coefficients ω_n are the quadrature weights and $I_{\nu n}$ the intensity at the quadrature point n which may be computed from the radiative transfer equation:

$$\frac{\partial I_{\nu n}}{\partial s} = k_{\nu n}(s)\,(I_\nu^0(s) - I_{\nu n}(s))\,. \quad (4)$$

It is then sufficient to store the values $k_{\nu n}$ for the seven quadrature points and for each band (the index n in $I_{\nu n}$ and $k_{\nu n}$ refers to the spectral band of width $\Delta\nu$), as functions of the thermodynamic conditions. In practice, instead of $k_{\nu n}$, the coefficients used are:

$$k_{\nu n}^* = k_{\nu n}\,\frac{T\,Q(T)}{x\,p} \quad (5)$$

where $Q(T)$ is the partition function of the considered molecule at temperature T, x is the mole fraction and p the total pressure. $k_{\nu n}^*$ has smoother variations with temperature than $k_{\nu n}$ and simple linear interpolations can be carried out. A detailed description of the CK parameters used in this study is given in [14].

The WSGG model is the most commonly used in engineering applications because of its simple implementation and small CPU times. The authors consider here for comparison the classical form of WSGG with three gray gases characterized by constant "absorption coefficients" and temperature-dependent weights plus one clear gas. In the case of spatially constant radiative properties, the radiative transfer problem reduces to the resolution of four transfer equations [19]:

$$\frac{\mathrm{d}I_k}{\mathrm{d}s} = \kappa_k\, x\, p\,(a_k(s)\, I^0(s) - I_k(s))\,, \quad (6)$$

$$I = \sum_{k=1}^{k=4} I_k \quad (7)$$

where κ_k and $a_k(s)$ are respectively the constant absorption coefficient and temperature-dependent weight of the k^{th} gray gas ($\kappa_4 = 0$, $a_4 = 1 - \sum_{k=1}^{k=3} a_k$), and $I^0(s)$ the total local equilibrium intensity which is equal to $\sigma \cdot T(s)^4/\pi$. I_k may be considered as the spectral part of the total intensity I in the regions of the spectrum where the absorption coefficient is close to $xp\kappa_k$. $a_k(T)$ is the fraction of the total intensity of equilibrium radiation, at the temperature of the emitting element, corresponding to the same spectral regions. With the same degree of approximation, the boundary condition for the gray gas k at a diffuse wall may be written

$$I_{kw} \equiv \varepsilon_w a_k(T_w) I^0(T_w) + \frac{(1-\varepsilon_w)}{\pi} \int_{2\pi} I_{k,inc} \cos\theta \, d\Omega \quad (8)$$

where ε_w, T_w and I_{kw} are respectively the wall emissivity, temperature and isotropic leaving intensity and $I_{k,inc}$ is the incident intensity in a direction characterized by θ. The model parameters κ_k and $a_k(T)$ are generally obtained by adjusting total emissivities $\varepsilon_g(T)$ to fit the expression:

$$\varepsilon_g(T) = \sum_{k=1}^{k=3} a_k(T)\,(1 - \exp(-\kappa_k x p l)) \quad (9)$$

for different xpl conditions. The main limitations of the WSGG model are the following: a) it is assumed when using equation (6) that absorption is accounted for with the weighting coefficient a_k taken at the temperature of the emitting medium; b) radiative properties of walls and eventual particles are necessarily gray; c) the model leads to an overcorrelation between emission at high temperature (in the band wings) and absorption when the absorbing regions are optically thick; d) the extension of the model to the case of mixtures with overlapping bands is not obvious, especially in the case of varying mole fractions. In this study the WSGG parameters are from Taylor and Foster [25].

3. Results and discussion

Coupled radiation and reactive fluid dynamics calculations are performed in the laboratory for an industrial glass furnace. The glass surface area is 80 m^2. The furnace is heated by seven natural gas ALGLASS™ burners installed on each side in a staggered configuration. A variable heat transfer coefficient on the glass surface is assumed with constant infinity glass temperature in order to take into account the presence of the batch, the foam and the bubblers. After having made calculation in the existing air-fired glass furnace, an oxy-firing modelling was performed in order to get the best future working state (burner positions, power distribution, etc.). In this context, coupled radiative calculations with fluid dynamics in the laboratory were made in both cases and using two gas radiative property models, i.e., the CK and the WSGG model. It should be noticed that the CK model calculation takes 70 times more CPU time than the WSGG model calculation.

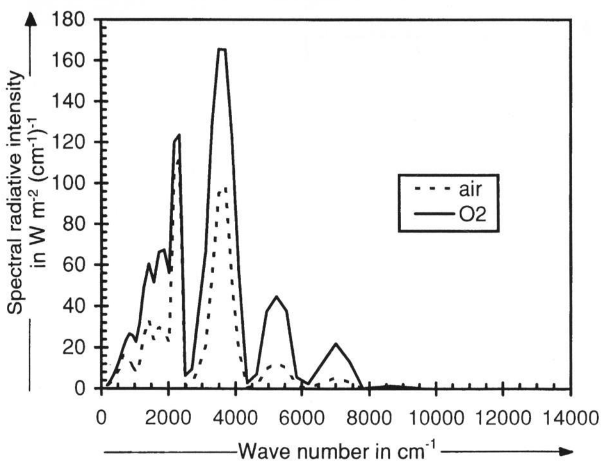

Figure 1. Spectral incident intensity, integrated over 2π steradian, from gases under a burner on a given point of the glass surface, without wall radiation, for air and oxy combustion,

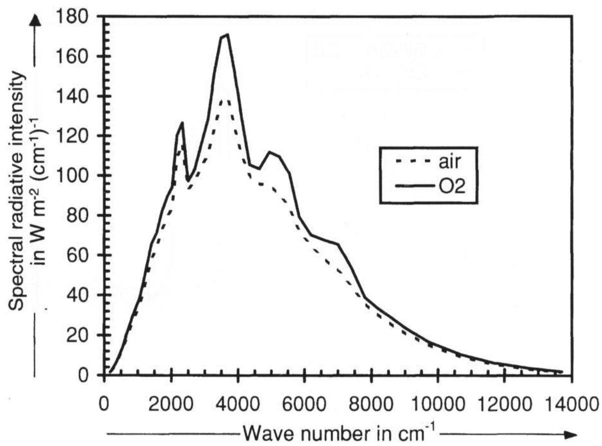

Figure 2. Spectral radiative intensity, integrated over 2π steradian, under a burner on a given point of the glass surface, with wall radiation, for air and oxy combustion.

Figure 1 shows spectral incident intensity, integrated over 2π steradian, from gases under a burner on a given point of the glass surface, without wall radiation. The spectral incident intensity is greater in oxy combustion than in air combustion due mainly to the higher concentrations of H_2O and CO_2 with oxygen. This leads to a 25% decrease in fuel consumption in oxy combustion, independently of ballast effect, due to the better radiative transfer to the glass. By integrating these incident intensities over the whole radiation spectrum, 210% more incident flux in oxy combustion than with air are obtained. As the walls contribute 78% of the glass incident flux in air combustion, and 67% with oxygen, the spectrum is smoothed by the great influence of wall radiation (assumed to be gray) as shown in figure 2. Consequently, in the oxygen case, the 210% more in-

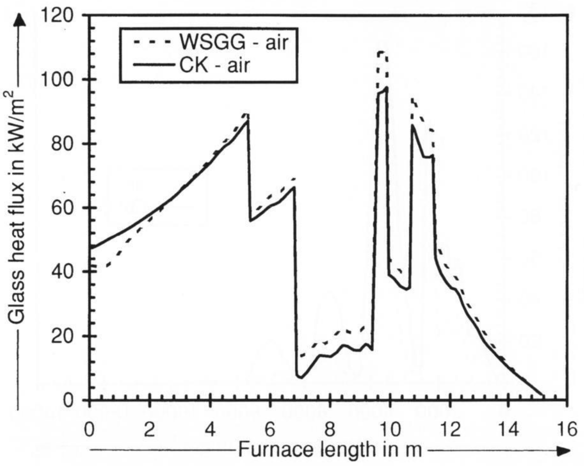

Figure 3. Heat flux calculated by CK and WSGG radiative models on the glass surface along the furnace axis, in the case of air combustion.

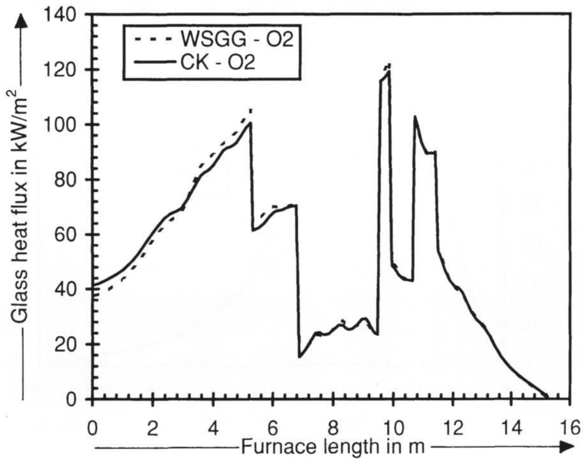

Figure 4. Heat flux calculated by CK and WSGG radiative models on the glass surface along the furnace axis, in the case of oxy combustion.

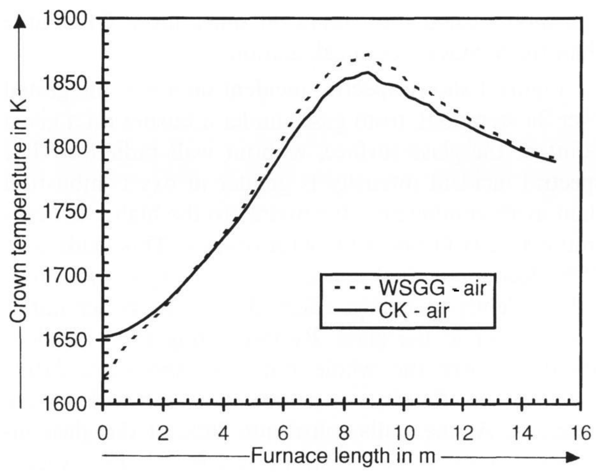

Figure 5. Crown temperature calculated by CK and WSGG radiative models on the glass surface along the furnace axis, in the case of air combustion.

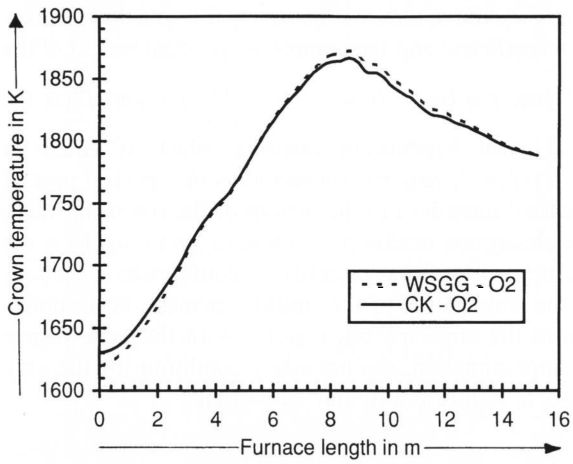

Figure 6. Crown temperature calculated by CK and WSGG radiative models on the glass surface along the furnace axis, in the case of oxy combustion.

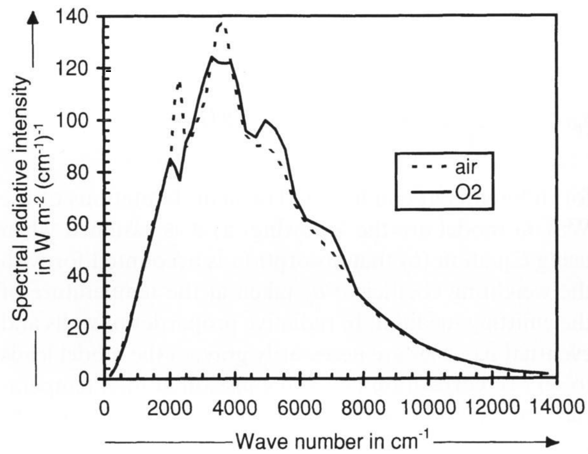

Figure 7. Spectral radiative intensity, integrated over 2π steradian, on a given point of the glass surface between two burners, with wall radiation, for air and oxy combustion.

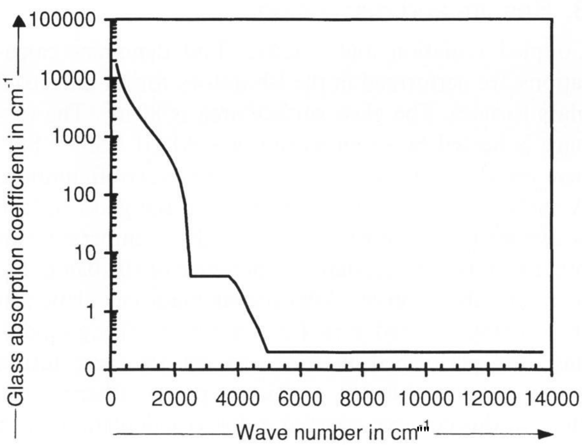

Figure 8. Spectral absorption coefficient of float glass.

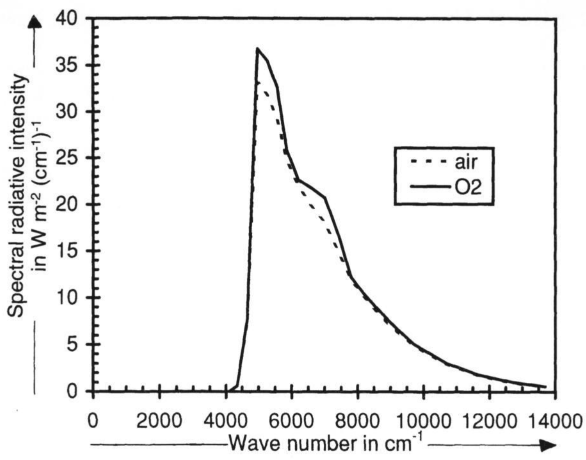

Figure 9. Spectral radiative intensity, integrated over 2π steradian, transmitted through 5 cm of glass thickness on a given point of the glass surface, between two burners, for air and oxy combustion.

cident gas flux compared with the air case becomes 15% of the radiative flux at the same point of the glass surface. Heat fluxes calculated by CK and WSGG radiative models on the glass surface along the furnace axis are displayed in figures 3 and 4 for air and oxy combustion, respectively. The relative difference between the local heat flux computed by the CK and the WSGG model can reach 90% in air combustion and 10% in oxy combustion, The great difference between the two latter values is due to the fact that the WSGG model is more valid in optically thick medium (oxy combustion) than in optically intermediate medium (air combustion). The calculated total heat power transferred to the glass depends on the radiative model used. In fact, in air combustion, the WSGG model overestimates by 4.5% the total heat power, compared with the CK model, while in oxy combustion, the total heat power overestimation reaches 1.8%. The crown temperature versus the furnace length is shown in figures 5 and 6. The difference between WSGG and CK models can reach 15 K in air combustion and 5 K in oxy combustion.

The spectral radiative intensity, integrated over 2π steradian, between two burners on a given point of the glass surface is shown in figure 7. At this point, the radiative flux is approximately the same for air and oxy combustion due to the peak of air absorption. But when taking into account the spectral float glass absorption coefficient (figure 8), the radiative flux transmitted through 5 cm of glass thickness at the same point on the glass surface is 8% higher in oxy combustion than with air as shown in figure 9. The difference between air and oxy combustion inside the glass could not be predicted with the usual method of Rosseland approximation.

4. Conclusions

A spectral radiation model (CK) in the ATHENA™ code has been developed. Coupled reactive fluid dynamics and radiation calculations are performed in an industrial glass furnace using CK and WSGG models with Taylor and Foster parameters The authors found that oxy combustion decreases fuel consumption in comparison with air combustion, due to better radiative transfer to the glass, independently of ballast effect. It is shown that the WSGG model overestimates the total heat power transferred to the glass with respect to the CK model, particularly in air combustion. In addition, important discrepancies in the local heat flux on the glass surface calculated by the CK and WSGG models are mostly observed in air combustion. On the other hand, the radiative transmission into the glass is spectrally different for air and oxy combustion and this leads to a different heat flux absorbed by the glass. The classical approach using Rosseland effective thermal conductivity in the glass fails to detect the latter results. The next step would be to use a spectral radiation model inside the glass bath, particularly in the case of clear glass, and to make coupled calculations with the spectral CK model in the laboratory for glass furnaces.

5. Nomenclature

5.1 Symbols

a	gray gas weight
g	cumulative distribution function
I	spectral radiative intensity in $W\,m^{-2}\,(cm^{-1})^{-1}$ integrated over 2π steradian
$k_{\nu n}$	absorption coefficient at wave number ν and for quadrature point n
$k(g)$	reciprocal function of the cumulative distribution function
K	absorption coefficient for real gas in m^{-1}
l	length in m
n	quadrature point
p	total pressure in Pa
Q	molecular partition function
s	curvilinear abscissa in m
T	temperature in K
x	mole fraction
$\Delta\nu$	bandwidth in cm^{-1}
ε	emissivity
κ	gray gas absorption coefficient in m^{-1}
θ	angle between the direction of propagation and the normal at the surface in rad
ν	wave number in cm^{-1}
σ	Stefan constant in $W\,m^{-2}\,K^{-4}$
τ	transmissivity
ω	Gauss quadrature weight
Ω	solid angle in sr

5.2 Superscripts

$\overline{\Delta\nu}$	averaged over the bandwidth $\Delta\nu$
0	equilibrium state
*	reduced coefficient

5.3 Subscripts

g	global
k	gray gas number
k,inc	incident and relative to the k^{th} gray gas
n	quadrature point
ν	monochromatic
ν,n	monochromatic and relative to quadrature point n
w	wall

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