

TURBULENT AIR PLASMA QUENCHING  
IN THE ENTRANCE REGION OF NARROW PASSAGES

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SUMMARY

The report presents experimental results on the heat transfer, quenching velocity and yield of nitrogen oxide in turbulent flows of air of 5000 K heated electrically from 10 to 1000 KW. Channels of different cross sections with equivalent diameters from 1 to 60 mm were studied with flow velocities 500 m/s and quenching velocities over  $10^7$  K/s. The results were interpreted by means of relations applicable for design engineering.

1. INTRODUCTION

Production of highly concentrated nitrogen oxide from air plasma flows demands quenching velocities over  $10^7$  K/s. It can be performed in recuperative heat exchangers with short narrow passage channels of different cross sections. Such constructions provide not only adequate increase rates of the heat transfer and of quenching velocity, (1), but also proper yield augmentations of nitrogen oxide (2) on the account of larger heat transfer surfaces and smaller cross section areas facilitating the fractional contribution of heterogeneous reactions in the process (3). Reliable analytical solutions are hardly possible for quenching with temperature gradients on the wall about  $10^5$  K/cm, leading to variable physical properties of the gases, because of the absence of reliable equations for the effects of turbulence, as well as of constants for the equations of the chemical reactions. To our knowledge, no complex experiments of

the process have been reported as yet, and a comparison of the results published by different authors is impossible because of the different stages studied and of the different experimental conditions used. An analysis of results was performed at the Institute of Physical and Technical Problems of Energetics, Lithuanian Academy of Sciences, on the basis of the vast experience and extensive experiments performed (4 through 6). The analysis revealed significant effects of the reference temperature chosen (4), reference dimension and physical properties of the gases, to reflect the effects of dissociation and of chemical nonequilibrium. Supplementally experiments were performed to find a relation of the quenching velocity (8) and the nitrogen oxide concentration.

## 2. EXPERIMENTAL

To find the determining factors of the high temperature heat transfer in quenching, a simplified case of steady-state flow was studied (4, 5) in a channel 21 mm in diam. This was followed by the heat transfer experiments in the entrance region of a circular pipe (5), as well as in annular and rectangular channels with different initial conditions. The air and the nitrogen were heated by a 1000 KW heater (9,10) providing steady - state continuous gas flows in the course of several hours.

A study of slot channels of equivalent diameters up to 4 mm (side ratios 1:10 and 1:40) was performed with a 30 KW electric arc heater with pressures up to 10 bar. Calorimetric measurements of the flow velocity and temperature profiles, nitrogen oxide concentrations, supplied data on the flow dynamics, and allowed a comparison with the results for thermal balance as a reliability test. Temperature measurements on the cooled walls by copper-constantan thermocouples provided accurate heat flux densities at the wall. The results were fed to an original data acquisition system at the rate of 12 items per s.

## 3. INTERPRETATION

Because of the considerable physical changes in gases in the range of temperatures studied, the reference temperature is a crucial problem. Our choice was based on the simplicity of the determination relations for different parameters, similar to those for the moderate temperature range. We succeeded in this for a non-dissociating steady-state flow to  $T_D$  admitted 2500 K for air and 4000 K for nitrogen, by referring the parameters to the bulk flow temperature  $T_f$  (5) and to pipe diameter  $d$ . The relation coincided with the one for pipe flows with different equivalent diameters (11):

$$Nu_{fd} = 0,019 Re_{fd}^{0,8} \quad /1/$$

For the coefficients of thermal conduction  $\lambda$  and dynamic viscosity  $\mu$  of air, which are included in the criterion of similarity (12,13), and analysis of earlier results (12, 13)

for temperature interval from 1000 to 2500 K suggested the following approximate equations:

$$\lambda = 4.83 \cdot 10^{-2} (0.40 + T/1000), \text{ W/(mK)}, \quad /2/$$

$$\alpha = 20.8 \cdot 10^{-6} (1.06 + T/1000), \text{ W/m}^2. \quad /3/$$

At the temperatures of dissociation, heat transfer coefficient is usually determined from complex thermal capacity and enthalpy difference, rather than temperature difference. An analysis of our data (6) for temperatures to 4000 K and 5000 K for air and nitrogen, respectively, revealed an alternative possibility of determining the heat transfer coefficient from the temperature difference and from the ratio of flow temperature  $T_f$  over dissociation temperature  $T_D$ , in the power of 0.9. The best agreement (for wall temperatures from 250 to 400 K) of eq. /1/ and the data for the heat transfer of dissociated gases was found by reference to frozen thermophysical properties. For air at temperatures up to 5000 K it coincided with /2/ and /3/.

Transient flow in the entrance region with different convergence angles  $\alpha^0$ , requires either specific factors (14) or separate calculations by the flat plate technique, to account for the effect. This is supported by constant velocity and temperature values along the channel axis for cooled walls (15). The parameters are here referred to the entrance flow temperature  $T_0$  and the distance from the entrance  $x$ . In slot channels of heights lower than 2 mm, account of the height should be made, together with the equivalent diameter

For the quenching velocity  $\psi$ , the most simple relation was based on the thermal balance in a pipe flow (8):

$$Ka = 4 \cdot \epsilon_w \cdot \epsilon_c \cdot Nu, \quad /4/$$

$$Ka = \psi \cdot d^2 / (\alpha \cdot T), \quad /5/$$

where  $\psi = w_0 \Delta T / x$  - quenching velocity, K/s,  $\alpha$  - thermal diffusivity,  $\text{m}^2/\text{s}$ ,  $\epsilon_w$ ,  $\epsilon_c$  - correction factors (8).

The results of nitrogen oxide concentration  $C_{\text{NO}}$  after quenching were interpreted in dependence of the entrance flow temperature  $T_0$  and of the channel diameter. Temperatures, corresponding to  $C_{\text{NO}} = \text{max}$ , are of utmost interest.

#### 4. RESULTS

Data on heat transfer (4) and quenching velocities in the range of temperatures and channel diameters studied, resulted in the following relation:

$$Nu_{fd} = 0.019 \cdot \epsilon_x \cdot \epsilon_h \cdot Re_{fd}^{0.8} (T_f/T_D)^{0.9}, \quad /6/$$

where a correction factor accounting for the entrance length  $x$  and convergence angle  $\alpha^0$  is determined by (14):

$$\epsilon_x = (1.32 + 0.00089 \alpha^0) (x/d)^{-(0.12 + 0.000367 \alpha^0)} \quad /7/$$

A correction factor for channel height  $h$  from 2 to 0.5 mm, for channel width  $b$  of 20 mm and length  $l$  of 100 mm studied, is (16):

$$C_h = 6.2(d_e/l)^{0.55} = 3.75(h/b)^{0.55} \quad /8/$$

With  $x/d_e < 2$  and high turbulence levels in the high temperature gas flows a 25 to 30 % over estimation is to be expected (6). Results for the entrance region of a passage, interpreted by the flat plate technique, yielded a simplified relation (6):

$$Nu_{xo} = 0.0255 Re_{xo}^{0.8} (T_o/T_D)^{0.9}, \quad /9/$$

except for flat slot  $h < 2$  mm passages.

Results on nitrogen oxide concentration (17, 18) in the optimal temperature about 3200 K, approach the analytical curve of the equivalent diameter function ( $d_e$ , mm) and is described by

$$C_{NO} = 4.4 \cdot d_e^{-0.09}, \quad \% \quad /10/$$

The relation is applicable for circular and flat passages. Here the quenching velocity is over  $10^7$  K/s, atmospheric pressure in the gas flow was maintained by means of mounting several passages of similar heights to increase the flow diameter. An increase of pressure results in higher yields, according to an earlier relation (1). With a decrease of temperature, nitrogen oxide concentration also decreases, but an increase of temperature over 3200 K leads to  $C_{NO}$  decrease for  $d_e > 2$  mm, and causes no significant change for  $d_e < 2$ .

## 5. CONCLUSIONS

1. By relevant interpretation techniques, heat transfer equations for channel flows in moderate temperatures /6 through 9/ can be extended to the high air temperature (to 4000 K) range.
2. Parameter calculations in air quenching must be referred to frozen thermophysical properties /2, 3/.
3. Nitrogen oxide concentration after recuperative quenching in channels is determined by the channel diameter and initial gases temperature /10/.

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