Plasma Plume Dynamics Metamorphoses during the Plume Laminar-Turbulent Transition

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Abstract
Three typical stages characterized by changes of the average exit enthalpy and stagnation point heat flux have been recognized. Measurements of the frequency spectra of the plume core optical emission are used to explain the phenomena of the interaction between the dynamic processes originating in the plume core mixing layer and plume core.

Introduction

The transformation of advanced technologies to reliable, more energy efficient, high volume manufacturing processes needs above all to advance the knowledge base of the plasma plume dynamics.

The plume dynamics influences in a decisive way the heat propagation phenomena through the plume, the mixing of the reactants with the plasma in a reactor as well as the particle dispersion injected into the flow - the most important events determining the effective utilization of the plume thermal energy in a specific technological process. However, the exact description of the plasma plume dynamics do not represent a simple task because the most plasma jet flows are neither laminar nor fully turbulent - they are usually transitional.

The identification of distinct plasma plume transition stages and the method of analysis of the mechanism controlling them.

The crucial role in a transitional - as well as in a turbulent plasma plume dynamics play the unstable plume shear layer and the vortex system evolving in it [1]-[6]. Essentially, there are three types of plume shear layer behavior - stages in the transition process [3]-[6]. Our particular approach in detecting and analyzing them is based on the analysis of the violent metamorphoses of heat propagation phenomena in the plume core [3]-[6]. They reflect the events governing the plume dynamics reliably and unambiguously. The needed information concerning plume heat propagation behavior are inferred from the stagnation point heat flux data measured in the plume core tip region [1][3]-[8] and from corresponding average enthalpies at the arc heater outlet on the one hand and on the other hand from oscillations of optical radiation emitted from the sensitive region of luminous plume core and of adjoined plume shear layer, reflecting the unsteady behavior of the plume shear layer vortex system.

The distinctive features of the stagnation point heat flux data in the plume core tip region (obtained by steady or unsteady heat flux probes [1][7][9]) along with corresponding data of arc heater exit enthalpies enable both to disclose the existence of the transition and to identify reliably the distinct stages of it [2][3][4]. On the other side the light oscillations emitted from the plume core region reflect both the dynamics of the heat propagation through the plume core and - accounting for the interplay between the unsteady shear layer vortex system morphology and the relevant thermal field "separation" disclosed by Eckert and Weise [9]-[11] - allow to detect the distinctive wave processes playing the dominant role in the plume transition dynamics and makes also possible to analyze the mechanism of their interaction.

This paper describes the mechanism governing the first and second stage of a plasma plume transition to the turbulence. Details of the used experimental equipment and diagnostic techniques may be found e.g. in [4]. Here we will only state that an argon plasma plume has been generated by a cascaded arc heater to establish fully controllable experiments in which the dynamic states of the plasma plume transition process could be unambiguously detected, quantified and reproduced.

The events controlling the plasma plume dynamics and relevant propagation phenomena in the course of plume transition to turbulence

Fig. 1 demonstrates in detail how the distinct transition stages are simply identified both by abrupt changes in the stagnation point heat fluxes and by the torch exit average enthalpies. Coincidentally with the onset of the second stage the maximum average exit enthalpy is attained and the final state of this stage limits the maximum heat flux produced by the plume.

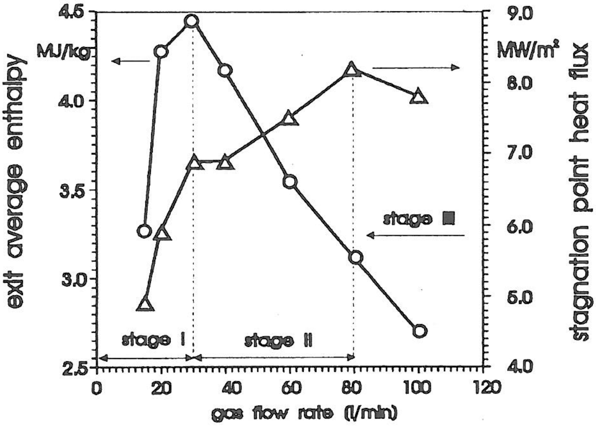

Fig. 1 Identification of distinct plume transition stages (arc current I=175A, length l=80 mm)

The corresponding sequences of oscillation of the plume core optical emission spectra in Fig. 2 and Fig. 3 show, how the distinct stages of the process scenario comprise the different types of the energy distributions between particular wave processes generated both by the plume mixing layer and by the plume core instabilities. As shown in Fig. 2, during the first process stage evolution the plume shear layer instability induces - through the feedback process - the global, jet mode oscillations of the plasma column.

The onset of the second stage (Fig. 3) occurs as the spectrum dominant frequency adjusts really to the "jet mode" frequency. With corresponding Strouhal number 0.22-0.23 values by the feedback induced plume core oscillations protrude into the arc chamber cavity. The arc column oscillations generate here the heat transfer increase to the cooled chamber walls and the arc heater average exit enthalpy decreases. Simultaneously, the column oscillations promoted by a feedback process stimulate the plume stagnation point heat flux increase. Its maximum value (Fig. 1) corresponds to the final state of the second transition stage.

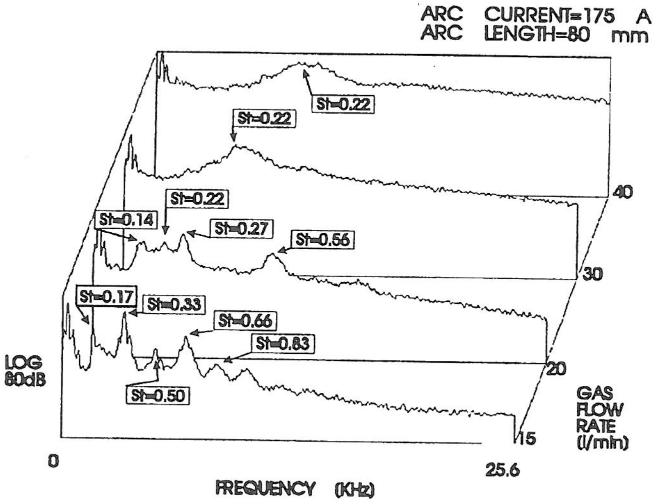

Fig. 2 Spectra of integrated light emitted from the sensitive region of a plume core as a function of gas flow rate (current I=175A, length l=80mm), stage I

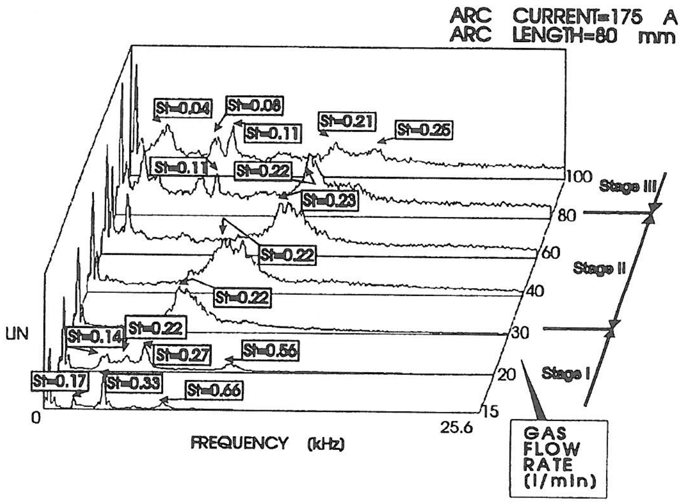

Fig. 3 Spectra of integrated light emitted from the sensitive region of a plume core as a function of gas flow rate (arc current I=175A, length of a chamber l=80mm), stage I-III

The third process stage is generated by the dominant "jet mode" wave energy redistribution into subharmonic modes - Fig. 3 and manifests itself as shown in Fig. 1 by a decrease of the plume stagnation point heat flux. As shown in detail in [4][5][6] the third plume transition stage is of a strong resonance nature. Simply, the thermal energy is pumped into the plume by the plume core helical oscillations driven by the arc chamber cavity acoustical resonance. At the onset of the third transition stage the maximum thermal energy is transported along the plume core axis. At the end of this stage where the flow is fully turbulent (self-sustained) the minimum amount of transported energy is minimal [4][5][6]. Thus, the distinct stages of the plasma plume transition scenario are controlled by a specific types of resonance between the particular wave processes produced by the plume mixing layer and plume core instabilities.

The above described resonances are also responsible for different heat propagation phenomena taking place in the plume during the transition process. The plume shear layer feedback, the plume shear layer- plume core subharmonic resonance and the acoustic resonance in the plasma column exhibit dynamically closed global behavior. Some features of a low dimensional dynamic systems might be considered to be included in the plume transition dynamic behavior. The light fluctuations emitted locally from a luminous plasma plume core manifest the same qualitative and quantitative behavior as wire anemometer data obtained during the adequate transition stages in a cold, low-density (e.g. helium) jets issuing into atmospheric air [12][13][14]. There is an important difference here, however. In contradiction to the cold, low-density jet, the design and operating parameters of the arc heater can affect the plasma plume transition process more considerably [16]. The scenario of the process remains, but the details, which concern e.g. the optimum choice of the plume heat transport behavior may be influenced substantially by simply changing the operating (arc current) or design (arc chamber length) parameters.

Conclusion

The phenomena controlling the transitional plasma plume dynamics are identified and analyzed. It is suggested that the transition process could be separated to three different stages. In the first stage the shear layer instability induces the global jet mode oscillations. The second stage is characterized by the penetration of the oscillations into the whole jet column and into the arc chamber cavity. The third, preturbulent, stage of transition is dominated by the spiral instabilities of the plume core. The similar dynamic scenario exhibits a transitional, cold, low density jet issuing into dense medium. Some features of the observed transition behavior suggest that the theory of nonlinear dynamic systems might be used successfully in formulating of the exact model of plasma plume dynamics. This research was funded by the Grant Agency of the Czech Republic (no. 202/93/0115).

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