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Transition of the electrohydrodynamic two-phase flow into the single-phase flow in a needle-to-plate negative corona discharge in the finite-volume chamber

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This work presents the instantaneous flow images and velocity vector field maps showing the temporal and spatial evolution of the electrohydrodynamic two-phase flow to the single-phase flow after the negative corona inception between the needle-to-plate electrode. The results showed that the EHD flow evolvement of the two-phase fluid can be divided into four transient two-phase structural stages, i.e. the free jet stage, the initial stage of wall-impinging jet, the development stage of wall-impinging jet and the fully developed EHD jet. The flow evolution ends with the single-phase steady-state due to the electrostatic precipitation of the incense smoke particulates.

1. Introduction

Motion of electrically charged fluids (gaseous or liquid) in an electric field is the subject of electrohydrodynamics (EHDs). When studying such fluids, it is convenient to distinguish two cases defined by the state of the fluid motion. The first case concerns the fluid being still (motionless) before subjecting it to the electric field. The second one corresponds to the fluid which is in motion before applying the electric field, forming the so-called primary fluid flow. The spatial structures of both fluids, the motionless and that being in motion, change significantly after applying the electric field.

The following considerations will be limited to the gaseous fluids, single-phase or multi-phase, which are initially motionless. An example of the electrically charged single-phase gaseous fluid is a single- or multicomponent gas in which a corona discharge has been induced. Air is the typical multicomponent single-phase gas. When the fluid consists of two or more matter phases, it is called a multi-phase fluid. An example of the two-phase fluid is the flue gas in electrostatic precipitators (ESPs), which can be regarded as a mixture of an after-combustion gas (a carrier fluid) and dust (a particulate dielectric matter) suspended in it.

Let us discuss shortly what happens when an electric field is applied to the initially motionless electrically charged single-phase or two-phase fluids The charging of the fluids can be carried out by another source before applying the electric field, or by the applied electric field itself, for example when after applying the electric field a corona discharge has been induced in the fluid.

In a motionless gaseous single-phase fluid, for example such as air, the forces exerted by the applied electric field on free electron and gaseous ions present in the fluid are transferred during collisions to the neutral molecules through the momentum transfer, setting the latter in motion. As a result a flow of the molecules appears, changing the previous motionless status of the single-phase fluid. This flow of the molecules is historically called the electric (or recently the ionic) wind (the discovery of the electric wind is credited to Francis Hauksbee (1709), while the name "electric wind" is attributed to Newton [1]). For the purpose of this paper we will call this electrodynamically induced flow of molecules an electrohydrodynamic (EHD) molecular flow to distinguish it clearly from an EHD particulate flow occurring in the gaseous

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two-phase fluid. The EHD molecular flow redistributes the electric charges in the fluid, which in turn modify the electric field in the fluid. Such a coupling of the electric field, the space charge formed by the electric charges [2–6] and the induced molecular flow causes that the EHD phenomena in the single-phase fluid are complex [7–9].

The EHD phenomena become even more complicated when the fluid consists of two matter phases. An example of such a fluid is an after-combustion gas with dust particulates suspended in it. After applying the electric field in the form of corona discharge in the motionless fluid consisting of a carrier fluid and particulate matter fluid, first the EHD molecular flow is formed. Then the particulate matter become charged by the gaseous ions and gets subjected to the electric field. Due to it the charged particles form its own EHD flow, which in principle may differ from that of the molecular EHD flow. As a result the EHD interactions include the electric field, the molecular space charge, the dust particle space charge, and two EHD flows: the EHD molecular flow and the EHD particulate matter flow. This makes the EHD flow of such a two-phase fluid very complex.

The above implies that in the initially motionless single- or two-phase fluids closed in chambers of finite volumes a relatively long transient processes occur after applying the electric field (e.g. in the form of corona discharge). More complicated situation can be expected after the corona inception in the initially motionless two-phase fluid closed in a finite-volume chamber. The transient phenomena will concern the concentration of the particulate matter, the electrical characteristics of the corona, and both EHD flows: the molecular and particulate matter flows formed in the chamber. First, due to the electrostatic precipitation the concentration of the dielectric particulate matter in the chamber will steadily decrease until all particulates deposit on the counter electrode and chamber walls. In this moment the fluid becomes practically single-phase and the single-phase steady-state regime is reached. Second, the corona current, which depends strongly on the concentration of particulate matter [10] will change until the single-phase steady-state regime is reached. Third, after the corona inception the EHD molecular and particulate matter flows will transform through several transition structures into their final form, i.e. the EHD molecular flow will take the final form typical of the single-phase fluid, while the EHD particulate matter flow will cease to exist. So, after the corona inception in the two-phase fluid closed in the finite-volume chamber we should observe the continuous transition from the two-phase fluid to the single-fluid, and the single-phase steady-state will be reached after the precipitation of all of the particulate matter, which takes a relatively long time.

Our preliminary experiments on the temporal and spatial development of EHD particle flow in an initially motionless two-phase fluid (air with suspended incense smoke particles) in the needle-to-plate corona discharge [11] suggested the existence of the transient EHD particle flow regime, which has been transforming through several structural stages into the single-phase steady-state regime (not reached in the experiment presented in Ref. [11]). These transient structural stages were: the two-phase (air-smoke particles) free jet stage (such name seems to be justified by the fact that the formation region of the free jet is far enough from the plate electrode wall to stay unaffected by it, at least in the initial phase of the free jet), the initial stage of two-phase wall-impinging jet, the development stage of two-phase wall-impinging jet and the fully developed two-phase EHD jet continuously evolving due to the precipitation of smoke particles into the single-phase (air) steady-state stage. The nomenclature used for naming the transient structural stages was derived by us from Refs. [12,13] since the transient structural stages of the transient EHD particle flow resemble those of a gaseous fuel wall-impinging jet injected by a high pressure into a combustion chamber [12], as well as those described in Ref. [13]. The flow structure of the two-phase free jet stage of the EHD particle flow recorded in our preliminary experiment [11] was difficult to explain on the basis of common understanding of the generation of EHD induced ionic wind in the negative corona discharges in electronegative gases (i.e. also in air). Our recent more accurate repetition of the preliminary experiment presented in Ref. [11] has revealed more details of the EHD particle flow in the two-phase free jet stage [14]. Namely, the high temporally-resolved recordings of the EHD particle flow images showed the formation of several EHD particle flow substructures simultaneously travelling along the interelectrode gap during the two-phase free jet stage.

This paper presents results of a high temporally- and spatially-resolved investigation of the transition of EHD two-phase flow to the single-phase flow after the negative corona inception between the needle-to-plate electrode in an initially motionless two-phase fluid (air with incense smoke particulates dispersed in it) closed in the finite-volume chamber. The studies were performed for the negative high voltage pulses rising linearly on the needle electrode to a certain value and then staying constant. This means that both regimes of the EHD two-phase fluid flow, i.e. the transient two-phase flow regime with all its stages and the steady-state single-phase regime could be studied in this experiment.

The results of investigations include instantaneous flow imaging and instantaneous velocity vector fields measured using 2D Time-Resolved Particle Image Velocimetry (TR PIV) method.

2. Experimental set-up

The experimental apparatus for the study of EHD two-phase fluid flow consisted of an acrylic box with a needle-to-plate electrode arrangement inside, high voltage supply, high-voltage probe, ammeter, digital oscilloscope and 2D TR PIV equipment.

The acrylic box (L:W:H = 600 mm: 120 mm: 50 mm), in which the needle-to-plate electrode arrangement was placed, was filled with still air with submicron incense smoke particles suspended in it (the size distribution of the incense smoke particles can be found in Ref. [15]). Before each measurement the box was filled with new air having the smoke particles homogeneously distributed in it. The initial concentration of the smoke particles was about $(450 \pm 50) \times 10^3$ particles/cm^3.

The needle-to-plate electrode arrangement consisted of two electrodes, a needle and a plate. The needle electrode was made of a stainless-steel rod (1 mm in diameter), the end of which had a tapered profile with the tip having a radius of curvature of 75 μm. The plate electrode was also made of a stainless-steel. The interelectrode gap was 25 mm. The negative high-voltage was applied to the needle electrode through a 3.3 MΩ resistor. The plate electrode was grounded.

The temporally-resolved measurements of the EHD two-phase fluid flow were carried out for a rectangular high voltage pulse rising linearly to a certain value and then remaining constant. The negative voltage pulse was generated by a high-voltage DC power supplier (Spellman High Voltage Electronics Corporation, SL50PN300). The rise rate of pulse front was 13.5 kV/s. The pulse amplitude was - 12 kV (measured between the needle electrode and the plate electrode using the high-voltage probe Tektronix, P6015A). After reaching the constant value by the voltage pulse the average corona discharge current was measured with the ammeter (Brymen, BM859CFa). We found that the average corona discharge current changed with decreasing concentration of the smoke particles, which have been continuously removed from the chamber volume due to the particle precipitation. It increased from about 15 μA at a particle concentration of 450 000 particles/cm^3 (the first