3D Acoustic Streaming Field in High-Intensity Discharge Lamps

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Abstract

Worldwide 19% of the electric power is consumed for lighting [1,2]. A considerable fraction of artificial light sources are high-intensity discharge (HID) lamps which are used for outdoor lighting, shop lighting, automobile headlights and other applications. Despite an increasing market share of light emitting diodes, HID lamps will be irreplaceable in the foreseeable future because of their superior color rendering index and their sun like luminance [3]. Although HID lamps have reached a certain stage of technical maturity, further effort is required in order to obtain lamps of highest quality and efficiency.

The left part of Figure 1 shows the design of an HID lamp [4]. A voltage applied to the electrodes inside the arc tube establishes a plasma arc of high temperature, which constitutes the source of light emission. To avoid electrode erosion and demixing of the arc tube filling, HID lamps are operated with alternating current. From the electronic point of view minimal material costs are achieved at the energetically optimal operation frequency of approximately 300 kHz [5]. Unfortunately, in this frequency range periodic heating due to ohmic loss excites acoustic resonances. The high frequency sound wave, however, causes a low frequency movement (ca. 10 Hz) of the plasma arc, visible as light flicker (Figure 1, right). It has recently been discovered that the acoustic streaming (AS) phenomenon is responsible for this link [6]. For further improvement of the lamp design a thorough understanding of the underlying mechanisms is crucial.

The investigation of light flicker in HID lamps requires a model that comprises equations for the determination of the electric potential, the buoyancy driven velocity field, the temperature field, the acoustic pressure and the sound driven fluid motion due to AS. In contrast to the time-dependent 2D model in [7], we use a stationary 3D model. Arc flicker shall be identified through instabilities of the velocity field, which is assumed to be a superposition of the buoyancy driven velocity field and the AS velocity field.

The temperature distribution inside the arc tube is determined from the conservation laws in Figure 2 and the temperature-dependent material laws [4]. The temperature field is used as input for the calculation of the acoustic eigenmodes. Subsequently, the acoustic pressure field at a resonance frequency is determined using a well-established method under consideration of various loss effects [8,9]. In a last step the streaming field is calculated (Figure 3). The sound particle

velocity associated with the acoustic eigenmodes does not include the effects of shear viscosity near the solid walls and, therefore, the oscillatory sound field cannot cause AS. To account for shear viscosity, the sound particle velocity is modified by the inclusion of an appropriate damping factor [10,11].

A highly coupled multiphysics model has been set up to calculate the AS velocity field inside the arc tube of HID lamps. The resulting velocity field is an important quantity for an understanding of the lamp behavior and a prerequisite for a forthcoming linear stability analysis, which will be used to identify light flicker.

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Figures used in the abstract

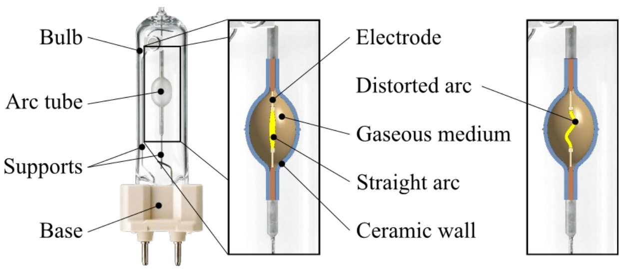

Figure 1: Left: Design of an HID lamp (Philips 35 W 930 Elite). Right: Arc perturbation in vertical lamp operation.

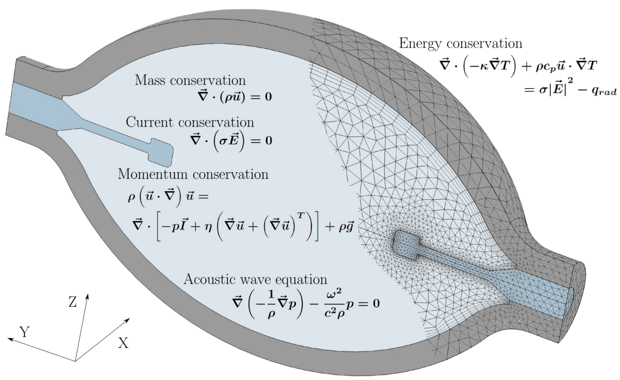

Figure 2: CAD half model of arc tube with an extract of the used finite element mesh. In addition, the differential equations are displayed.

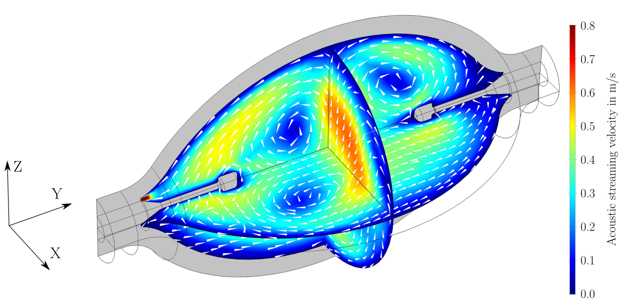

Figure 3: Streaming field in the arc tube at the f = 47.1 kHz resonance.