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Evaluation of heat transfer coefficient of tungsten filaments at low pressures and high temperatures

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ABSTRACT

The paper presents an experimental method for the evaluation of the heat transfer coefficient of tungsten filaments at low pressures and high temperatures. For this purpose an electrode of a T5 fluorescent lamp was tested under low pressures with simultaneous heating in order to simulate the starting conditions in the lamp. It was placed in a sealed vessel in which the pressure was varied from 1 kM (kilo micron) to 760 kM. The voltage applied to the electrode was in the order of the filament's voltage of the lamp at the normal operation with the ballast during the preheating process. The operating frequency ranged from DC to 50 kHz. The experiment targeted on estimating the temperature of the electrode at the end of the first and the ninth second after initiating the heating process. Next, the heat transfer coefficient was calculated at the specific experimental conditions. A mathematical model based on the results was developed that estimates the heat transfer coefficient. The experiments under different pressures confirm that the filament's temperature strongly depends on the pressure.

1. Introduction

Recently, a better understanding of the heat transfer from wires and fibers into gases or plasma (and vice versa) has been recognized as an important field of investigation [1]. Almost all the experimental researches deal with gas flow in a tube of small diameter with an outer cooling system. In the tube there is a metallic filament or fiber which undergoes a thermal change and its cooling or heating rate is measured. It is well known that experiments in an exactly static atmosphere suffer errors and inaccuracies of the recording instruments and their readings, because the temperature difference between the wire and its surroundings causes a relative gas flow over the hot wire.

In the present work a study was carried out for evaluating heat transfer in natural convection processes at wires used in light bulbs under low pressure. Fluorescent lamps use electric discharge to produce light. A moderate high-frequency voltage of a few Volts is applied to the electrodes at both ends of a straight or curved tube. The tube is under low pressure of approximately 1 mBar. The discharge is usually attained after a small period of preheating the electrodes. This time ranges from 0.5 to 2 s. Preheating the electrodes to a temperature of 1000 K or higher, prior to ignition, initiates the discharge and protects the electrodes from losing their emitter mixture [2–4]. During the preheating period, the electrodes are heated and the acquired temperature depends on the heat transfer from the filaments to the gas mixture into the bulb. The whole phenomenon is dominated by the natural convection flow conditions.

It is well documented that, depending on the applied voltage, the ambient temperature and the electric resistance of the electrode, the achieved electrode temperature remains constant. Furthermore, it is known that for stable gas temperature and provided that the mean free path of gas molecules or atoms is much larger than their diameter, electrode's thermal conductivity and heat transfer coefficient are independent of the gas pressure. Fluorescent tubes contain a mixture of inert gasses such as neon and argon in addition to a few milligrams of mercury. The atomic diameter (Van der Waals radius is about 1.4–1.55 nm) of these gasses is much smaller than their mean free path (10^5 nm) at the low pressure of the tube. In such conditions, the variation in the tube pressure results in electrode temperature diversities during their preheating. This leads to the reduction of lamp life if the pressure is higher or lower than the manufacturer's recommended value. In this study is presented an experiment which shows the dependence of the electrode current on the pressure of gases in the tube. This is due to the change of the electrical resistance of the electrode under different pressures. The change in the electrical resistance is attributed to the change of the overall heat transfer coefficient on account of the change of the pressure. An informative diagram, related with filaments at different low pressures, is

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presented in [5] showing the dependence of electrode temperature (brightness temperature) on the argon pressure in the tube, when low current flows through the electrode.

Lamp electrodes are heated during preheating process applying AC voltage or current of constant amplitude, depending on the selected scenario from the manufacturer. In this study the constant voltage procedure was implemented. During this procedure, there is a short time delay for the current to stabilize, because its magnitude depends on the electrode temperature. Eventually, the current stabilizes when equilibrium is achieved between the electrode power supply and the heat transfer from the electrode to the gas atmosphere surrounding it. At low pressures a few days are required for accurate equilibrium [4,6,7], but for the precision of this study it is accepted that the stabilization of the current occurs in a few seconds.

During preheating if the heat transfer coefficient is high enough the electrode temperature falls. This results in lower electrical resistance of the electrode which permits more current flow.

Taking into account the above considerations, for a given applied voltage to the electrode, by measuring one of the parameters, such as the electrode current, the electrode resistance or its temperature, the other two can be evaluated. It is important for the lamp life that the electrode heating process reaches a temperature of at least 1000 K. The temperature of the lamp cannot be measured directly, because of the fluoresced material already in the inner surface of the tube. Instead, the voltage and current can be measured at the end of the preheating procedure and from Ohm's law the corresponding (hot) resistance is evaluated. Since the value of the cold resistance of the electrode is known, the hot to cold resistance ratio (preheat ratio) is calculated. Preheat ratio is then used to compute the electrode temperature from a known formula or from available Tables where the electrode material is tabulated.

In this study the preheating conditions in a fluorescent lamp were simulated using real lamp electrodes. Fluorescent lamps' electrodes are made of tungsten wire covered with a mixture of barium, calcium and strontium carbonates. These carbonates, which are decomposed to oxides during lamp operation, do not contact the electric current but they facilitate the discharge process. The electrodes were placed in a chamber in which various pressures were applied under DC and AC voltage and their temperature was calculated. The results show that the value of the pressure significantly influences the electrode temperature. It is believed that these results will provide a better understanding of both the fluorescent lamp preheating process and gas properties of heat transfer.

2. Experimental method

2.1. Test device

A schematic of the experimental apparatuses is shown in Fig. 1. Three lamp electrodes were placed in a sealed vessel. The filaments were removed from the interior of broken T5 fluorescent linear lamps. This type of fluorescent lamp is recently replacing T8 or T12 types; hence it is of great interest to know their characteristics [8]. The breaking of the tubes was made smoothly by applying an incremental voltage to a wire of Nickel–Chromium alloy coiled around the tube. The filaments were placed in the vessel protruded, in order to exchange heat with their environment freely. Two of them were almost identical. They were taken from T5-14 W lamps. The third one was from a T5-24 W lamp. The electrodes were initially heated for several minutes in nitrogen atmosphere at about 500 °C in order to reduce the strains in them. One of the three electrodes was used for the measurements. The other two were tested many times on secondary measurements in order to verify the results and check the conclusions for any potential errors.

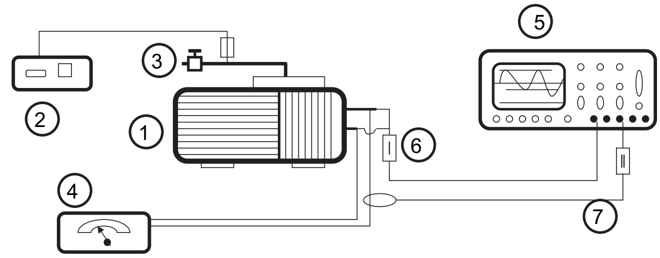

Fig. 1. Experimental setup for low pressure heating study. 1. vessel, 2. vacuum gauge, 3. filling/evacuating hole, 4. waveform generator/amplifier, 5. oscilloscope, 6. current probe, 7. differential probe.

The apparatus which was used to put the electrodes in was able to inhibit the suction of the air when it was under low pressure. It was a semi-hermetic reciprocating refrigeration compressor emptied from its electrical components. The three end caps with the lamp pin contacts were mounted on the lampholders which, in turn were connected with the six terminals of the 3-phase compressor. Its internal diameter was 162 mm and its external diameter was 200 mm. The internal length of the chamber was 175 mm, plus its mechanical department. Fig. 2 presents the inner part of the compressor with one electrode at the test position. This wiring made from the compressor's manufacturer, ensured the tightness of the chamber with regard to the connection of the inner part of it with the outer one. After the electrodes had been fixed, the chamber was evacuated to a pressure of 1 kM (equals 1 Torr) and remained for one day without increasing it, thus ensuring the mechanical seal leakage. Then the vessel was filled with nitrogen up to atmospheric pressure and was evacuated again. Thus, the clearness of nitrogen was guaranteed. In the course of the experiment, when the system was to be stored the apparatus was filled with nitrogen up to a pressure of 760–800 kM inhibiting the inflow of air.

In this study the electrodes' current was measured under atmospheric or sub atmospheric pressures while a DC or constant AC voltage was applied. A vacuum pump was used to rarefy the nitrogen atmosphere in the vessel. Nitrogen or other inert gas is used in high temperature experiments to protect the filaments from fracture. The TIF 9450D vacuum gauge was used for measuring the pressure which was controlled with a vacuum pump. This gauge measures pressure in microns (M) or kilo microns

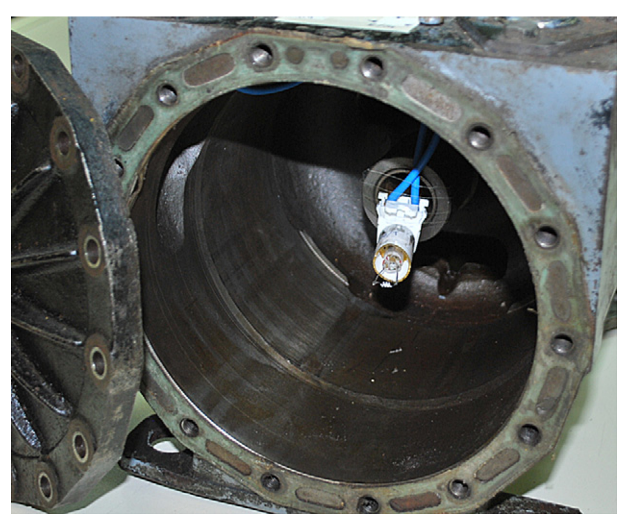

Fig. 2. The interior of the vessel with one electrode.