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International Journal of Heat and Fluid Flow 26 (2005) 709–721
International Journal of
HEAT AND FLUID FLOW
www.elsevier.com/locate/ijhff

An experimental investigation of fluid flow and wall temperature distributions in an automotive headlight

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Received 11 October 2004; received in revised form 12 February 2005; accepted 15 May 2005
Available online 11 July 2005

Abstract

Detailed measurements of wall temperatures and fluid flow velocities inside an automotive headlight with venting apertures are presented. Thermocouples have been used to characterize the temperature distributions in the walls of the reflectors under transient and steady operating conditions. Quantification of the markedly three-dimensional flow field inside the headlight cavities was achieved through the use of laser-Doppler velocimetry for the latter condition only. Significant thermal stratification occurs in the headlight cavities. The regime corresponding to steady operating conditions is characterized by the development of a vortex-dominated flow. The interaction of the main vortex flow with the stream of colder fluid entering the enclosed volume through the venting aperture contributes significantly to increase the complexity of the basic flow pattern. Globally, the results have improved the understanding of the temperature loads and fluid flow phenomena inside a modern automotive headlight.

Keywords: Automotive headlight; Headlamp cavity; Natural convection; Internal heat source; Wall temperature; Laser-Doppler velocimetry

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1. Introduction

In recent years, extensive changes have been introduced in the design of automotive front lighting systems. Some of these changes are clearly visible, but there have also been more subtle transformations conferring additional functions to modern automotive headlights such as adaptive lighting capabilities. On the other hand, lighting systems have evolved from a nearly exclusive technical purpose to become an integral component of vehicle styling. This has brought into play various conflicts, namely technical requirements versus styling aspects and innovation versus regulations (Huhn, 2002). In particular, the demand for more compact designs, employing lightweight and recycling materials, has made the task of achieving thermal performance in headlights more and more difficult to fulfill.

The use of lightweight materials in headlight assemblies has allowed manufacturers to compensate for the increase in weight imposed by the growing complexity in design. The replacement of glass by semi-transparent polycarbonate in the front lens of a headlight is perhaps the most conspicuous example of this practice. Moreover, the use of molded plastic compounds in headlight assemblies is the rule nowadays. As the application of these materials is constrained by limited ranges of temperature, temperature loads in the headlight must be carefully taken into account in the design process. The consequences of unsuitable choices made at this stage include long-term damage to various plastic parts due to high-temperature stresses and a reduction of the light

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0142-727X/$ - see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.ijheatfluidflow.2005.05.003

Nomenclature

g	gravitational acceleration
k	thermal conductivity
L	length scale of the cavity
Q	volumetric heat source
Ra	Rayleigh number, $g\beta\Delta TL^3/(\alpha\nu)$
Ra'	modified Rayleigh number, $g\beta QL^5/(\alpha\nu k)$
T	time-averaged temperature
U, V, W	time-averaged velocity components of the fluid
X, Y, Z	space coordinates

Greeks

α	thermal diffusivity
β	thermal expansion coefficient
ν	kinematic viscosity

Subscripts

amb	ambient
max	maximum

bulbs lifespan. This potentially results in poor lighting performance and, eventually, premature failure of the headlight.

Another important aspect to take into consideration is the fact that, contrary to older-style headlights, modern plastic-made headlight assemblies are not hermetically manufactured. Venting apertures are usually installed in order to allow for expansion and contraction as the air within the light chamber heats and cools. However, this also means that air is permitted to be exchanged with the atmosphere. As a result, moisture may enter and, given the appropriate conditions, condense on internal surfaces. This is undesirable as it may have an impact on both the normal operation of the headlight (e.g., compromising the beam pattern, oxidizing electrical connections) and on its aesthetic appearance (Bielecki et al., 2003). On the other hand, sensible placement of the venting apertures may generate an airflow pattern that sweeps away the condensation in a very efficient manner as the headlight warms up. Additionally, stagnant internal fluid areas can be minimized and a clever design will also take advantage of this airflow to cool down the hot parts.

Nevertheless, the main flow inside a headlight is not generated by the vents. The presence of thermal sources (i.e., the light bulbs) inside the headlight cavities gives rise to the establishment of internal buoyancy-driven circulations. Similarly, and on the topic of electronic components packaged within an enclosure (see a review by Incropera, 1988), buoyancy forces induce a recirculating flow within the enclosed space and heat transfer occurs by natural convection. However, the role of conduction and, especially, radiative heat transfer cannot be disregarded in the analysis of the present case. The interaction of the aforementioned recirculating flow pattern with the stream of external air entering the vents, and the geometric intricacy of modern headlight casings, further contribute to the increased complexity of this subject.

The investigation of natural convection in porous cavities with internal heat generation has received particular attention in the last few years as a consequence of its wide range of applications (many references; see e.g. Jue, 2003). However, the fundamental physics of the foregoing subject differ significantly from that of simple air-filled (no porous material) enclosures containing internal thermal sources. For the latter class of problems, Yerkes and Faghri (1992) determined the effects of mixed convection on the flow structure of large baffled chambers. Sun and Emery (1997) studied the effects of wall conduction, internal heat sources and a baffle on natural convection heat transfer in a rectangular box. More recently, a two-dimensional enclosure containing internal heating elements (either two vertical plates or a rectangular block) was investigated numerically by Barozzi and Corticelli (2000). These three examples provide relevant information for the understanding of fluid flow and heat transfer phenomena in vented automotive headlights but still constitute crude simplifications of the actual physical scenario.

Successful attempts to numerically simulate automotive headlights have been made by Moore and Powers (1999) and Moore et al. (1999), using finite element analysis methods for solving coupled specular radiation and natural convection with an unstructured computational mesh. Recent simulations, also employing sophisticated computational fluid dynamics (CFD) tools, have been carried out by Chenevier (2001), Wulf and Reich (2002) and Halgren and Hilburger (2003). In addition, Shiozawa et al. (2001) and Okada et al. (2002) have presented CFD predictions together with very limited measurements of fluid flow inside the headlight (in a plane adjacent to the surface of the lens only) using particle image velocimetry (PIV). Overall, these studies have shown that a good correlation between simulations and experiments can nowadays be obtained. However, it is evident that the success of the aforementioned numerical simulations relies heavily on the availability of detailed experiments. Hence, the scarcity of experimental data and the need for a better