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Effect of light penetration depth during laminar mixed convection in a discretely, asymmetrically and volumetrically laser-heated vertical channel of finite length

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ABSTRACT

Particle image velocimetry (PIV) measurements are carried out in an experimental investigation of laminar opposing mixed convection in a vertical flow cell of finite length with a square cross-section. The bulk downward flow is driven by gravity while a portion of a lateral side is heated with laser irradiation. The working fluid is a copper nitrate aqueous solution, and the experiments are performed for three values of the Reynolds number of $Re = 20$, 40 and 60 and three values of the nondimensional absorption coefficient of $a^* = 0.5$, 4.2 and 6.7. These parameters correspond to modified Richardson number range from 67 to 8084. A parametric study has been carried out to assess the effect of light penetration depth (i.e. absorption coefficient or solution concentration) on the final flow configuration; shear stress distributions have been calculated from the velocity field. Numerical simulations are also carried out to determine the thermal distributions, local and overall nondimensional heat transfer rates (Nusselt numbers) along the irradiated cell wall, and the complex flow features are presented in the form of contours of velocity, vorticity and temperature. The results reported herein demonstrate the modulation effect of Re and a^* on the flow and temperature distributions, and explore the convenience of laser irradiation heating for the purpose of selectively localizing energy deposition during thermal therapies by modeling biological tissues as light-absorbing media.

1. Introduction

Pulsed lasers have found important applications, among other areas of medicine, in dermatology. Vascular lesions are different types of abnormal blood vessels within skin for which patients seek treatment. The theory of photothermolysis [1] has made laser treatments possible; the basic concept is to denature the proteins of the blood vessel with an appropriate temperature increase by selective laser irradiation of the abnormal blood vessel while thermal damage to the surrounding tissue is avoided. Such heating is accomplished irradiating skin with a laser wavelength which is preferentially absorbed by the blood vessel to be treated compared with other chromophores in skin, melanin for example. Important parameters to select the laser wavelength, fluence and pulse duration for a specific treatment are the blood vessel diameter and depth location. Shorter wavelengths are suited for small and superficial blood vessels while longer wavelengths are the choice for larger and deeper veins [2]. To improve the effectiveness of selective phothermolysis-based treatments, it has been proposed to combine laser heating with mechanical, optical and biochemical approaches; for the specific case of Port Wine Stains (PWS) see [3–5].

Laser pulse energy coupled to hemoglobin originates convection heat transfer from the hot blood to the blood vessel wall and then conduction to the surrounding tissue. If the temperature increment achieved by the blood vessel wall is high and long enough, proteins denature and the blood vessel is destroyed. Such convective effects are more important for deep and large diameter vessels (leg veins up to 4 mm in diameter), compared with smaller and superficial lesions (0.1 mm in diameter telangiectasias). For the latter, because of its short thermal relaxation time, heat is transferred to the surrounding tissue before the entire laser pulse is coupled to the blood vessel and the desired temperature increment never occurs [1]; photomechanical means to destroy the vessel have been proposed to overcome this issue [2].

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