Abstract

Natural convection in non-Newtonian fluids is extensively studied due to its inherent advantages and industrial relevance. At practical temperature differences, the Oberbeck-Boussinesq (OB) approximation fails, and temperature dependent effects, also called non-Oberbeck-Boussinesq (NOB) effects, become quite significant. While substantial research considering NOB effects in Newtonian fluids has been carried out, only a handful of studies account for these effects in non-Newtonian fluids. Most studies neglect important temperature dependencies and consequently their accompanying implications.

In this study, an Order-of-Magnitude-Analysis (OMA) was employed to identify significant temperature dependent thermophysical properties for two classes of commonly encountered non-Newtonian power-law fluids. The identified dependencies were incorporated into the governing equations to arrive at a set of NOB equations valid over a practical range of temperatures. The equations were solved numerically for three specific problems to investigate the extent of NOB effects on the flow field, consequent heat transfer and Nusselt number trends.

Insight to the underlying physics of combined NOB effects and non-Newtonian behavior was gained by revisiting the classical vertical flat plate problem. Shear thinning significantly augmented the NOB effect of accelerating the flow field to over double that for the equivalent Newtonian case. The corresponding inaccuracy in estimated heat transfer exceeded 30 percent. On the other hand, shear thickening diminished the extent of acceleration due to NOB effects by up to half. Further implications of this differential extent of augmentation due to shear thinning and thickening were investigated by studying a fin array problem and curved plate problem. As these geometries additionally affected local shear rate distribution, the results of parameter optimization for heat transfer were significantly changed and even completely reversed in some cases. Furthermore, qualitative changes in Nusselt number trends were observed, which have implications for heat transfer correlations. Thus, the paradigm in which optimization and correlation studies in natural convection of non-Newtonian fluids are carried out needs to be carefully reconsidered in light of the present work to ensure that the obtained results adequately represent actual scenarios.

Keywords: consistency index; limiting criteria; non-Newtonian; non-Oberbeck- Boussinesq; order of magnitude analysis; temperature dependent; thermal expansion coefficient; thermophysical properties