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# Laminar flow and forced convective heat transfer of shear-thinning power-law fluids in dimpled and protruded microchannels

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ABSTRACT

The three dimensional laminar flow structures and forced convective heat transfer of shear-thinning power-law fluids in dimpled and protruded microchannel were investigated in this study. The CMC (Carboxyl Methyl Cellulose) aqueous solutions with various concentrations were employed as the working substances. The dimples and protrusions with relative depth $\delta/D$ of 0.1, 0.2 and 0.3 were vertically aligned to arrange on the opposite walls. The results reveal that the modes of separation flow near protruded walls, observed at some cases with $\delta/D = 0.2$ and 0.3, obviously differ from that near dimpled walls. Both the scale and intensity of all the separation bubbles are strengthened with the increase of flow rate and CMC concentration, except 4000 ppm. While, the results at cases of 4000 ppm show the variable geometrical structure of protrusion can overcome the negative effect of large CMC concentration on heat and mass transfer. Moreover, the heat and mass transfer of main flow and near-wall flow, as well as the strengthened secondary flow in the passage, are enhanced by the dynamic viscosity distinction of working substance, differing from the Newtonian flow. Furthermore, relative Fanning friction factor $f/f_0$ increases with the increase of depth of dimple/protrusion and flow rate and the decrease of CMC concentration. Relative Nusselt number $Nu/Nu_0$ continuously increases with the increase of flow rate and depth of dimple/protrusion. And then the maximum and minimum thermal performance *TP* are observed at the case 2000 ppm with $\delta/D = 0.3$ and CMC100 with $\delta/D = 0.1$, respectively. At last, new correlations of $f/f_0$ and $Nu/Nu_0$ are proposed based on the results in this study with a well-established data fitting.



## 1. Introduction

The shear-thinning power-law fluids are commonly encountered in many industrial practices, such as the petrochemical and chemical engineering, power engineering, pharmaceutical, biological, and food industries. With the development of heat exchanger in the above-mentioned engineering applications, the requirement of large heat removal with lower pressure penalty conducted by shear-thinning power-law fluids has become urgent [1]. Moreover, due to the high viscosity level, these working substances are mostly in the laminar flow regime. And then, the traditional heat transfer enhancement techniques of shear-thinning power-law fluids no longer works in some applications. Therefore, the studies of laminar flow and forced convective heat transfer of shear-thinning power-law fluids combining with flow control devices for heat transfer enhancement have been proposed and developed.

The investigations about flow and heat transfer of shear-thinning fluids have been conducted widely. Ternik [2] simulated the planar sudden symmetric expansion laminar flow of shear-thinning fluids, and the results showed the pressure gradient and flow resistance increased comparing with Newtonian fluid, also, the vortices length was greatly affected by shear-thinning behavior. Manica and De Bortoli [3] found that the critical Reynolds number, when the recirculation occurred, was lower for shear-thinning than that for Newtonian fluid. Attia [4] studied the unsteady flow and heat transfer of non-Newtonian fluids, including shear-thinning fluids, above a rotating disk, and the effect of non-Newtonian flow behavior on flow structures and temperature distribution were discussed. Barkhordari and Etemad [5] investigated the slip flow and thermal fields of shear-thinning fluids in microchannels. The increasing slip coefficient resulted in increasing of local Nusselt number, and this effect was enhanced as power law index increases. Peixinho et al. [6] experimentally studied the forced convection heat transfer of non-Newtonian flow in transitional periodic pipe. The results showed that the non-Newtonian behavior stabilized the flow, so the critical Reynolds number

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**Nomenclature**

| | |
|---|---|
| $C$ | specific heat (J kg$^{-1}$ K$^{-1}$) |
| $D$ | dimple/protrusion print diameter (μm) |
| $D_h$ | characteristic length, hydraulic diameter |
| $f$ | fanning friction factor |
| $H$ | microchannel height (μm) |
| $h$ | heat transfer coefficient (W m$^{-2}$ K$^{-1}$) |
| $K$ | consistency index (Pa s$^n$) |
| $n$ | flow behavior index |
| $Nu$ | Nusselt number |
| $P$ | fluid pressure (Pa) |
| $Pr$ | Prandtl number |
| $q''$ | heat flux (W m$^{-2}$) |
| $Re$ | Reynolds number |
| $T$ | temperature (K) |
| $TP$ | thermal performance |
| $U_{ave}$ | average velocity of inlet (m s$^{-1}$) |
| $\Delta P$ | pressure drop (Pa) |
| $\Delta T$ | mean temperature difference (K) |

*Greek symbols*

| | |
|---|---|
| $\delta$ | dimple/protrusion depth (μm) |
| $\lambda$ | fluid thermal conductivity (W m$^{-1}$ K$^{-1}$) |
| $\rho$ | fluid density (kg m$^{-3}$) |

*Subscripts*

| | |
|---|---|
| $out$ | outlet |
| $w$ | wall |

increased with shear-thinning. Tso et al. [7] investigated the laminar flow and heat transfer of shear-thinning fluids between parallel plates, and the results showed flow behavior had great effect on the heat transfer performance. Sasmal and Chhabra [8] studied the laminar natural convection flow and heat transfer of square cylinder submerged in static power-law fluids. The results showed heat transfer enhancement was obtained in shear-thinning fluids cases, even increasing by 100%. Primenta and Campos [9] studied the laminar heat transfer and friction factor of CMC (Carboxyl Methyl Cellulose) aqueous solution, the typical shear-thinning fluids, in a helical coil, and obtained the much lower friction factors. Singh et al. [10] investigated the hydrodynamic of CMC aqueous solutions flow in a novel coiled flow inverter, and the effects of CMC concentration on the pressure drop were discussed in detail. The shear-thinning behavior of special fluids has great influence on the flow structure and heat transfer, comparing with Newtonian fluids, and then the heat transfer enhancement with low pressure penalty can be expected.

Microchannel heat sinks are effective for heat and mass transfer removal, with large convective heat transfer coefficient [11–13]. Recently, novel designs and flow control technologies have been fulfilled in the microchannels to achieve higher heat transfer enhancement, and the results showed strip-fins [14], wavy microchannel [15], flow obstructions [16], bifurcations [17,18], truncated double-layered [19], porous fin [20] and dimples/protrusions [21,22] were beneficial, especially the dimples/protrusions [23]. Dimples and protrusions are useful for heat transfer enhancement with low pressure penalty in micro and mini-channels. The studies of heat transfer performance of minichannel with dimples showed the heat transfer coefficients increased to some extent [24,25]. Wei et al. [26] studied the heat transfer enhancement of microchannel with dimple for the first time, and the formation and development of separation flow and secondary flow in the passage were discussed, moreover, the pressure drop was indentified to equal to or less than that of smooth microchannels. The authors [27] investigated the laminar forced flow and heat transfer enhancement of a dimpled/protruded microchannel, and the detailed flow structures and performance parameters varying with physical properties and geometrical structures were analyzed, finally the correlations of friction factor and Nusselt number were obtained. Furthermore, we conducted the thermal performance of water in microchannels with grooves and obstacles in the laminar region. The results showed the combination structures of grooves and obstacle was beneficial for heat transfer enhancement [28]. We also experimentally studied the thermal performance and friction characteristics of non-Newtonian fluids in regular rectangular channels with dimples and protrusions, in which xanthan gum solution, Carbopol 934 solution and polyacrylamide solution were selected as working substances. The results showed that the combination of xanthan gum solution, a typical shear-thinning fluid, and dimple/protrusion gave rise to the heat transfer enhancement [29]. The previous works show that dimples/protrusions are effective heat transfer enhancement method for microchannels, as well as in the shear-thinning fluid cases.

The previous literatures show that enhanced heat transfer with low pressure penalty can be expected by means of the combination of microchannel heat sinks with dimples/protrusions and shear-thinning power-law fluids. And, CMC aqueous solutions is the typical shear-thinning power-law fluids, which can be beneficial for the flow resistance performance. More work about the heat transfer enhancement in microchannel using CMC aqueous solutions is needed to obtain great development accordingly. Therefore, in what follows, the laminar flow structures and heat transfer characteristics of CMC aqueous solutions (100–4000 ppm) in the microchannel with dimples and protrusions ($\delta/D = 0.1$–$0.3$) vertically aligned to arrange on the opposite walls under various flow rate ($Q = 3.72$–$8.69$ m s$^{-1}$) are analyzed in detail in this research.

## 2. Solution methods

### 2.1. Physical properties of working substances

In this study, CMC aqueous solutions, shear-thinning power-law fluids [30], are employed as working substances. All physical properties, except the dynamic viscosity, are considered as constant. Table 1 lists the values of the flow behavior index ($n$) and the consistency index ($K$) of CMC aqueous solutions at various concentrations [31], while the physical properties of the CMC solutions are listed in Table 2 [32]. It must be noted that the temperature difference of flow field is lower and the potential effects of the temperature-dependent thermophysical properties can be decoupled in this study.

**Table 1**
Flow parameters of CMC aqueous solutions [31].

| Concentration/ppm | $n$ | $K \times 10^3$/Pa s$^n$ |
|---|---|---|
| 100 | 0.9512 | 3.83 |
| 500 | 0.8229 | 8.49 |
| 2000 | 0.7051 | 27.92 |
| 4000 | 0.6161 | 657.2 |