Heat Transfer and Pressure Drop Characteristics of Hybrid Al_2O_3-SiO_2

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ABSTRACT

The emergence of Proton Electrolyte Membrane Fuel Cell (PEMFC) is seen as one of the greener alternatives to internal combustion engine (ICE) in automotive industry nowadays. However, the sensitivity of a PEMFC membrane needs to be further improved for the optimum performance. In this study, single and hybrid nanofluids are used as an alternative coolant in a single channel of PEMFC. The study was conducted in a channel with the adoption of single and hybrid nanofluids to observe the effect of the heat transfer and pressure drop in the set up. A heater pad was kept at constant heat load of 100 W, reflecting the actual heat load of a single cell. The study focuses on 0.5% volume concentration for single and hybrid nanofluids of Al_2O_3 and SiO_2 in water. The numerical study was conducted via ANSYS FLUENT 16.0. The 0.5% hybrid Al_2O_3:SiO_2 nanofluids of 10:90 and 30:70 in Re range of 300 to 1000 were compared to the base fluid. The heat transfer increament of 9.1% and 9.85%. was observed. However, the pressure drop was also increased in the range of 22 Pa to 26 Pa for 0.5 % of Al_2O_3:SiO_2 of 10:90 and 30:70 consecutively as compared to the base fluid. The advantage ratio was then analyzed to show the feasibility of both ratios of 0.5 % hybrid nanofluid of Al_2O_3:SiO_2 at 10:90 and 30:70. It shows that both have advantage ratio higher than 1, thus feasible for the adoption in a PEMFC.

Keywords: *Alumina oxides; Heat transfer; Hybrid; Pressure drop; Silicone dioxide*

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Introduction

The Proton-exchange membrane fuel cells (PEMFC) is one of the fuel cells categories which is favorable for automotive sector. The PEMFC has an advantage of high-power density, rapid response to change in loads, low operating temperature of 60 to 80 °C and its rapid start up [1]. The effective cooling is important to ensure that the proton exchange membrane fuel cell (PEMFC) is safe and operate efficiently, particularly when it comes to the higher fuel cell stack capacity. However, there are still some issues in the thermal management of PEMFC adoption which need to be resolved critically due to the sensitivity of its membrane as one of the vital components in its operation [2]. Besides the improvement in thermal management, many researchers nowadays are exploring possibilities to miniaturize the PEMFC cooling system in order to make it more attractive for commercialization [1]. Among the advancement are optimizing the design of the cooling path, the flow field and enhancing the heat transfer coefficient of its cooling medium [2]. The passive way of improving the PEMFC cooling medium property is through the adoption of nanofluids which seems to be a better way of thermal management without having to sacrifice the size of the cooling system of fuel cells [2-3].

Nanofluids is an engineered fluid which comprises of nano sized particles dispersed in its base fluid [3]. Nanofluids are primarily a dispersion of both metallic and non-metallic solids which is magnitudes higher in thermal conductivity as compared to base fluid [4]. Nanofluids is also capable of increasing the thermal conductivity of its base fluid due to increase in the total surface area of the nanoparticles [5]. In comparison to distilled water, a significant heat transfer coefficient improvement of 18 % was achieved through the nanofluids [6]. However, unlike adoption of nanofluids in other heat transfer application, PEMFC cooling fluids not only has to be high in thermal conductivity but at the same time maintaining the strict limit of its electrical conductivity value of 5 μS/cm [4]. This is required as to avoid shunt current while operating the stack and also power leakage to the conductive coolant [7]. There are a lot of heat transfer improvement performed utilizing different types of nanofluids such as ZnO, TiO_2, SiO_2 and Al_2O_3 [8–10].

A lot of research works has been established in the adoption of nanofluids to PEMFC. Zakaria et al. [11] was among the pioneer in the study and managed to established a correlation between thermal conductivity and electrical conductivity of Al_2O_3 in PEMFC. The study reported that there was an increment of 12.8 % in thermal conductivity and 14.8 % increment in electrical conductivity. There are various numerical and experimental works conducted to justify the feasibility of nanofluids adoption in PEMFC [10-12]. The performance of nanofluids was also studied in both plate and stack level of PEMFC [12–15]. It was reported that nanofluids has managed to improve

the heat transfer in a 1.5 kW_e Ballard PEMFC with almost negligible power drop with due to higher value in electrical conductivity nanofluids but is still acceptable with respect to overall stack output [14].

Research in nanofluids has evolved from a single nanofluids to both hybrid and tri-hybrid nanofluids in which the thermal conductivity was observed to be further improved [16-17]. Nabil et. al [20] has reported an increase of 22.8 % in thermal conductivity of TiO_2-SiO_2 hybrid nanofluids as compared to the base fluid. Saifudin et. al [5] on the other hand has managed to establish a performance enhancement ratio termed as PER for Al_2O_3-SiO_2 hybrid nanofluids in both thermal conductivity enhancement over electrical conductivity and viscosity penalty in PEMFC application. The study reported that the most feasible Al_2O_3-SiO_2 hybrid nanofluids mixture ratio was 10:90 and 30:70 for PEMFC application.

In this study, the established work of Saifudin et. al [5] is further investigated numerically. This work complemented the thermo-physical properties level of the study through the adoption of the Al_2O_3-SiO_2 hybrid nanofluids in a channel. This study add application value to the thermo-physical characterization done by Saifudin et. al [5]. The stainless steel channel was used to simulate a single channel in the PEMFC cooling plate. The channel was then subjected to a constant heat flux to replicate the heat released during the reaction in the bipolar plates of PEMFC. Two recommended mixture ratios as proposed in the previous work was studied which were 10:90 and 30:70 Al_2O_3-SiO_2 hybrid nanofluids in water. The base fluid of water, single nanofluids of Al_2O_3 and SiO_2 were also simulated as a cooling medium in the channel. At the end of the study, and advantage ratio was established to justify the feasibility of the adoption in PEMFC channel.

Methodology

Nanofluid thermo physical properties measurements

Thermal conductivity and viscosity of the nanofluid and base fluid used in this simulation were calculated at 30°C.

The density of nanofluid is calculated by using Equation (1):

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_p \quad (1)$$

The density of hybrid nanofluid is calculated by using Equation (2):

$$\rho_{nf} = (1 - \phi)\rho_f + \phi\rho_{p1} + \phi\rho_{p2} \quad (2)$$

The specific heat of nanofluid is calculated by using Equation (3):

$$C_{p,nf} = \frac{(1-\phi)\rho_f C_f + \phi \rho_p C_p}{\rho_{nf}} \quad (3)$$

The specific heat of hybrid nanofluid is calculated by using Equation (4):

$$C_{p,hnf} = \frac{(1-\phi)\rho_f C_f + \phi_{p_1}\rho_{p_1} C_{p_1} + \phi_{p_2}\rho_{p_2} C_{p_2}}{\rho_{hnf}} \quad (4)$$

Where ϕ was alluded as the proportion of particles by volume and the addendums f, p_1, p_2, b_f and h_{nf} were alluded as base liquid (water), Al_2O_3 and SiO_2 nanofluids and mixture nanofluid. Table 1 lists the nanofluid properties that were measured and determined.

Table 1: Nanofluid and base fluid properties used in numerical analysis

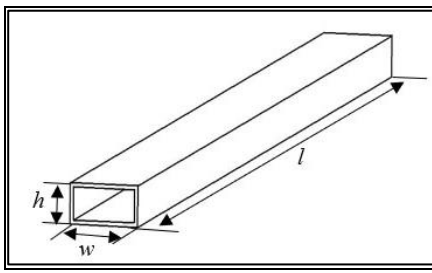
Fluid Name	Thermal Conductivity,K (W/mk)	Specific Heat,Cp (J/kg.k)	Viscosity,μ (Pa.s)	Density,ρ (kg/m^3)	References
Al_2O_3 0.5% conc.	36	765	-	4000	[11]
SiO_2 0.5% conc.	1.4	745	-	2220	[12]
Water	0.615	4180	0.000854	999	[11]

PEMFC channel mathematical model

A 3D Computational Fluid Dynamic (CFD) was established on the basis of a channel dimension as shown in Figure 1. As for the channel, the material used is stainless steel to imitate the channel of PEMFC. The dimension of channel is 20 mm x 10 mm x 380 mm. A consistent heat source of 100 W was implemented to the channel. There have only been a few assumptions [21]:

i. Incompressible, laminar and steady state flow.
ii. Body force effect is neglected.
iii. Viscous dissipation is neglected.
iv. With a relative velocity of zero, the fluid and nanoparticles are thermally balanced.

For computing in modelling, the channel has the same heat transfer and fluid flow characteristics.



Parameter	*Dim (mm)*
h	10
l	380
w	20

Figure 1: The schematic diagram of channel in PEMFC.

The following are the governing equations for the assumptions:
Equation for continuity:

$$\nabla.(\rho_{nf}.V_m) = 0 \tag{5}$$

Equation for momentum:

$$\nabla.\left(\rho_{nf}.V_m.V_M\right) = -\nabla P + \nabla(\mu_{nf}.\nabla V_m \tag{6}$$

Coolant energy equation:

$$\nabla.(\rho_{nf}.C.V_m.T) = \nabla.(k_{nf}.\nabla T) \tag{7}$$

Conduction of heat through a solid wall:

$$0 = \nabla.(k_s.\nabla T_s) \tag{8}$$

At the wall, there is a no-slip boundary:

$$\vec{V} = 0 \ \ (Walls) \tag{9}$$

The following boundary conditions were assumed at the channel inlet:

$$\vec{V} = V_m \ (inlet) \tag{10}$$

$$P = atmospheric\ pressure\ (outlet) \tag{11}$$

Heat is transmitted through the solid and distributed through the channel by forced convection of cooling liquid.

$$-k_{nf}.\nabla T = q \text{ (Bottom of channel)} \quad (12)$$

$$-k_{nf}.\nabla T = 0 \text{ (Top of channel)} \quad (13)$$

The analysis of heat transfer and fluid flow

Using this equation, heat transfer coefficient can be determined (14):

$$h = \frac{q}{\Delta T} \quad (14)$$

The Nusselt number can be calculated by using this Equation (15):

$$Nu = \frac{hl}{k} \quad (15)$$

The pressure drop can be calculated by using this Equation (16):

$$\Delta P = P_i - P_o \quad (16)$$

The pumping power can be calculated by using this Equation (17):

$$W_p = \dot{Q}.\Delta P \quad (17)$$

The advantage ratio can be calculated by using this Equation (18):

$$AR = \frac{h}{\Delta P} \quad (18)$$

Results and Discussion

Validation of the study

Prior to analysing the heat transfer and pressure drop effect of hybrid nanofluids, the simulation was first validated to ensure its accuracy against experimental data. The simulation data shows an acceptable accuracy value which was in the range of 2.47 % 2.82 % as shown in Figure 2. The small deviation shows that the simulation was reliable and further analysis then can be carried out.

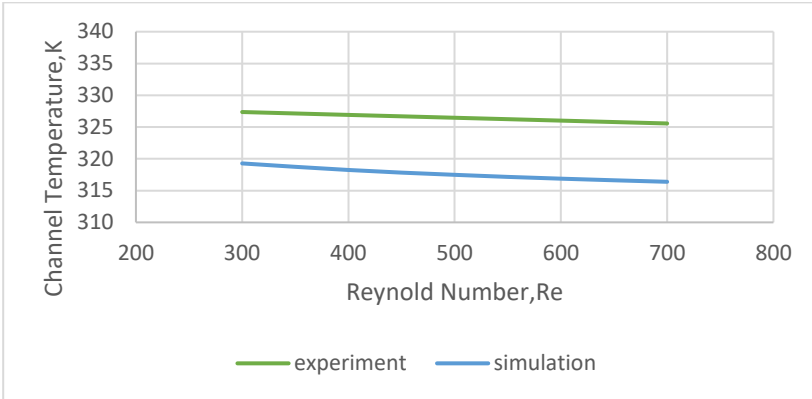


Figure 2: Base data validation.

Average channel temperature

When opposed to water as the base fluid, nanofluids also reduced total channel temperature. The highest improvement in the average channel temperature is given by the hybrid nanofluid with the ratio of 30:70 (Al_2O_3:SiO_2) with 2.57 % improvement as compared to base fluid of water as exhibited in Figure 3. This is followed by hybrid nanofluid of 10:90 (Al_2O_3:SiO_2), single nanofluid SiO_2 with the 0.276% lower compare to base fluid while the lowest average temperature is lower compared to the base fluid. This is due to the accumulation of nanoparticles in the fluids, which vastly enhance thermal conductivity while compared to the base fluid [22]. The use of two different nanoparticles in a fluid seeks to enhance thermal conductivity even more. This was proven by the improvement obtained in hybrid nanofluids with the ratio of 30:70 which has the lowest average channel temperature as compared to the rest of the fluids studied. The lower heat transfer in hybrid nanofluids is caused by the Brownian motion of both 13 nm Al_2O_3 and 30 nm SiO_2 nanoparticles [3]. The contact surface area of hybrid nanofluids has increased as a result of the smaller nano-sized particles, which has enhanced heat transfer. It was also discovered that as the number of Re grows, the average temperature of the channel decreases.

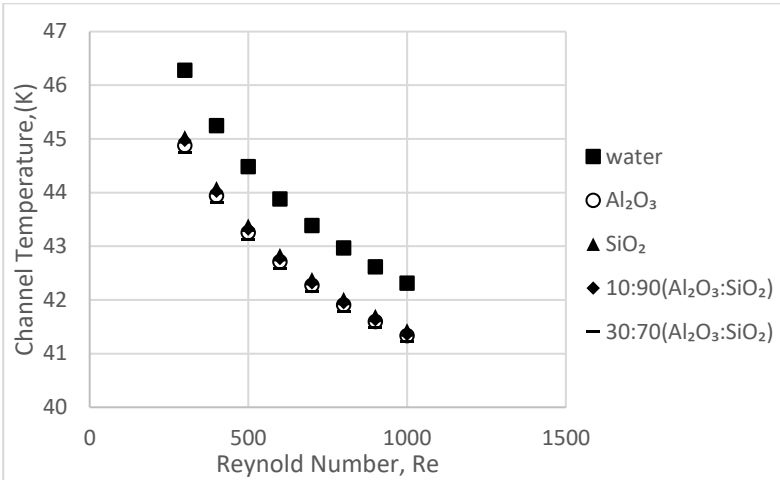


Figure 3: Average channel temperature with the adoption of nanofluids.

Heat transfer coefficient effect

The channel temperature was then converted to a heat transfer coefficient to determine a moving fluid's convective heat transfer ability. The higher convective heat transfer will give better heat transfer result. The highest heat transfer coefficient at Re 1000 is shown in Figure 4, was given by 0.5% of hybrid 30:70 Al_2O_3:SiO_2 nanofluid with 9.851% higher than the base fluid. As the ratio of nanofluids changed and Reynold number increased for all hybrid Al_2O_3:SiO_2 nanofluids, the heat transfer coefficient also increases. The addition of two nanofluids between Al_2O_3 and SiO_2 has enhanced thermophysical properties such thermal conductivity, specific heat capacity and others [6].

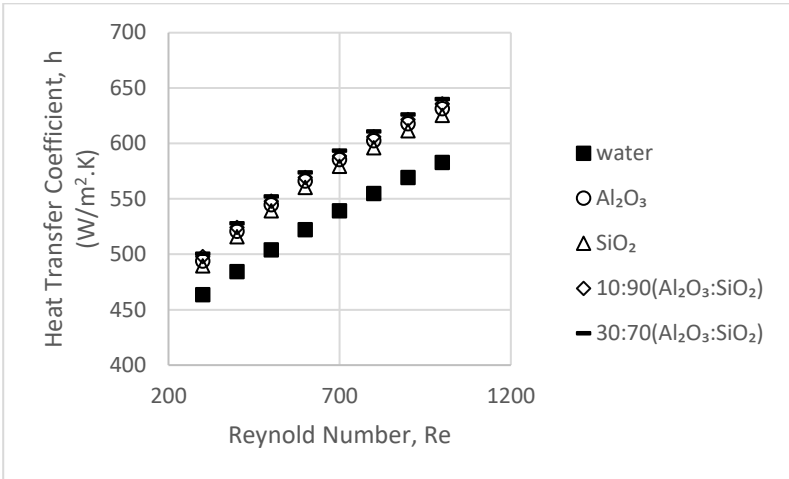


Figure 4: The graph of heat transfer coefficient against reynold number.

Nusselt number

Figure 5 indicates that as the Reynold number increases, the Nusselt number increased with it. To calculate the Nusselt number, convective heat transfer is necessary. There is a trend of lower Nusselt numbers for both hybrid nanofluids than single Al_2O_3 and SiO_2 nanofluids. This is because the hybrid nanofluids have lower thermal conductivity value compared to single Al_2O_3 and SiO_2 nanofluids. The highest Nusselt number for 0.5% concentration hybrid 10:90 Al_2O_3:SiO_2 nanofluids with 3.945% compared to the base fluid.

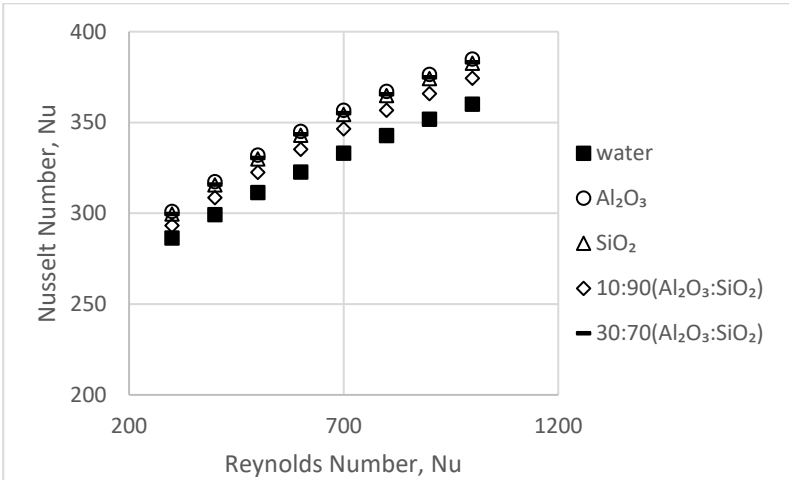


Figure 5: The graph of nusselt number against reynold number.

Pressure drop

The use of nanofluids in the channel, as seen in Figure 7, has an impact on the pumping power result. The pressure drop graph was plotted against the Reynold number is shown in Figure 6. The high-pressure will force the fluid to pass through the channel. The result of the pressure is as expected due to the need of fluid to flow in channel [13]. At a Re number of 1000, the highest pressure drop was measured at 0.5% Al_2O_3 with a 30:70 ratio, which was 26.468913 Pa higher than the base fluid. The single nanofluid of 0.5% concentration Al_2O_3 shown as the second highest pressure drop at Re number of 1000 which was 25.546417 Pa. The higher increment in pressure drop of hybrid nanofluid is shown compared to single nanofluids.

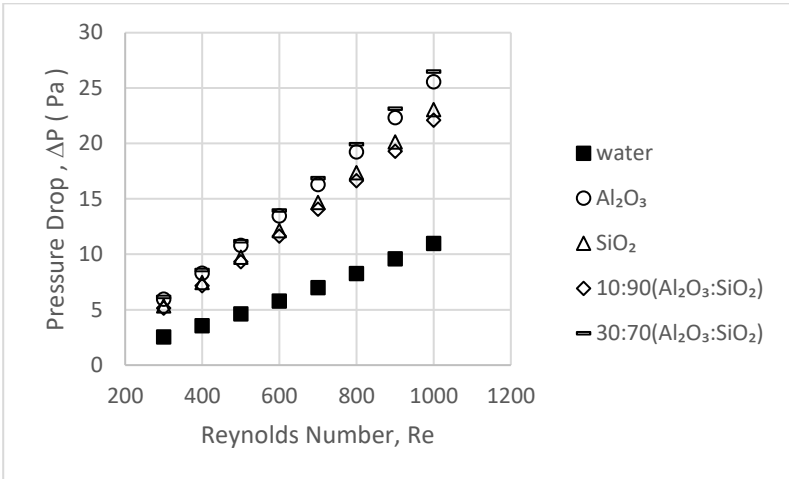


Figure 6: The graph of pressure drop against reynold number.

Pumping power

The higher pumping capacity is due to higher density and higher viscosity, resulting in a greater decrease in pressure [13]. As for single nanofluids, the pumping power was 0.5% concentration of Al_2O_3 at Reynold number of 1000 with w.564 times increment compared to the base fluid. Meanwhile, for hybrid nanofluid, the highest pumping power was 0.5% concentration Al_2O_3:SiO_2 with a ratio of 30:70 at Reynold number of 100 with 3.756 times increment compared to the base fluid. Figure 7 illustrates the use of nanofluids in the channel, which has an effect on the pumping power result.

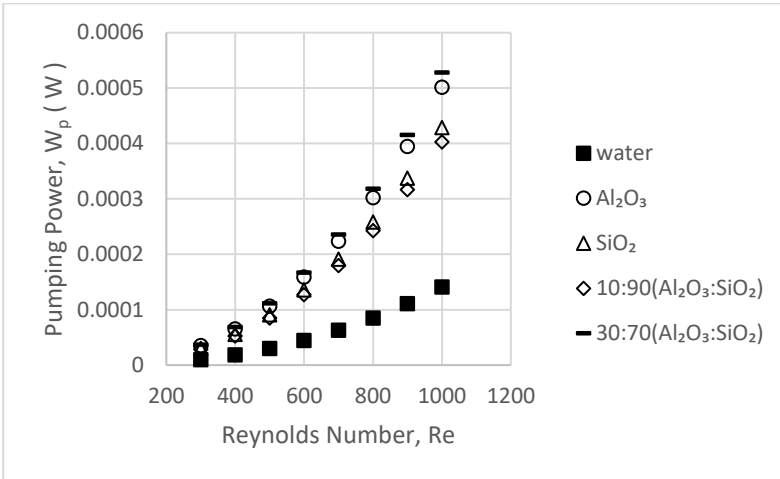


Figure 7: The graph of pumping power against reynold number.

Advantage ratio

The advantage ratio was calculated and shown in Figure 8 to ensure the feasibility of both single and hybrid nanofluid adoption in the channel of PEMFC. The advantage ratio was found to be highest at the lowest Reynold number for all coolants tested. This is due to decreased pressure encountered at a lower Reynold number, as opposed to the higher Reynold number. Compared with nanofluids, the base fluid was shown to have a higher advantage ratio. The advantage ratio for hybrid nanofluids used were greater than 1 at the whole Reynold number range from 300 to 1000. Azmi et al. claim that [7], for both improvements in the application of heat transfer and pressure drop factors, an advantage ratio greater than one should be conceivable.

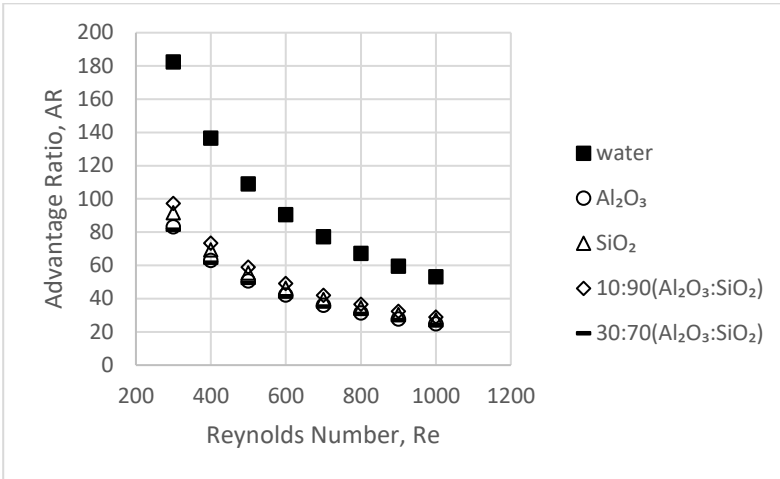


Figure 8: The graph of advantage ratio against Reynold number

Conclusion

The heat transfer and pressure drop characteristics of Al_2O_3:SiO_2 nanofluids in water were presented in this numerical analysis. The results showed there is an enhancement in all hybrid nanofluids compared to the base fluid. The improvement demonstrates this enhancement in terms of heat transfer coefficient and pressure drop. Since hybrid nanofluids in the channel undergo a higher pressure drop, the pumping capacity increases. Further correlation was then established which was termed the advantage ratio. This ratio, which includes both heat transfer enhancement parameters and increased pressure drop, justifies the viability of using hybrid nanofluids as a channel coolant. All hybrid nanofluids used in this study found advantageous adoption in PEMFC with advantage ratio values greater than 1 in all Reynold numbers.

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