DNS study by a bilayer model on the mechanism of heat transfer reduction in drag-reduced flow induced by surfactant

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- Heat transfer reduction
- Direct numerical simulation
- Compact difference scheme

A B S T R A C T

A bilayer model proposed in [1] is used to investigate the mechanism of heat transfer reduction of surfactant-induced drag-reducing channel flow with a constant heat flux imposed on both walls by direct numerical simulation. In the bilayer model, Newtonian fluid and viscoelastic fluid are assumed to coexist with shear stress balance satisfied between the two fluid layers. A Giesekus model is used to model the viscoelastic fluid induced by the addition of surfactant additives. High-order compact difference schemes are applied to discretize the convective and diffusion terms whereas MINMOD scheme is used to discretize the convective terms in the Giesekus constitutive equations to enhance numerical stability. The effectiveness of the surfactant additives at different flow region on heat transfer reduction is investigated.

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1. Introduction

It is well known that the addition of a small amount of surfactant additives into turbulent pipe flow may remarkably reduce friction drag, increase flow rate and/or decrease pressure drop. The drag reduction produced by surfactant additives when applied in industry can bring tremendous economical and social benefits. However, accompanied by drag reduction, heat transfer of the fluid is also reduced because of dramatic suppression of turbulence by surfactant additives [2–5]. The significant reduction of heat transfer rate can affect the efficiency of heat exchanger and decrease the performance of the heat transfer system and therefore deteriorate the capacity of the entire system. Efforts should be made to control the heat transfer reduction appropriately to minimize the negative effect of surfactant additives. In order to precisely control turbulent heat transfer, at the first stage how heat reduction is affected by additives at different flow region should be understood. It is interesting not only in terms of scientific research but also from the standpoint of engineering application.

In 2005 a DNS study on turbulent heat transfer of a drag-reducing fluid was first carried out by Yu et al. [6], in which a viscoelastic Giesekus model was employed and most of the experimental phenomena were successfully reproduced. The mechanism of heat transfer reduction in drag-reducing flow was discussed. Later, Kagawa et al. (2008) [7] performed a DNS of viscoelastic drag-reducing fluid flow accompanied by heat transfer at isoflux wall condition. Three cases of high heat transfer reduction rate were simulated and the effect of surfactant additives at different rheological parameters was identified. The total thermal resistance, inverse of Nusselt number, was determined by two components calculated quantitatively, which clarified the mechanism of heat transfer reduction. This kind of analyses were performed by Fukagata et al. (2005) [8] to analyze the contribution of turbulent heat flux to the Nusselt number in turbulent Newtonian channel flow. Through the analyses, they proposed a strategy examined by DNS for the simultaneous control of turbulence.

Till now, all the DNS studies on turbulent heat transfer reduction of drag-reducing flow by surfactant additives assumed that network structures were formed by surfactant additives existing in a whole flow region at a same concentration. In fact, the network structures are not distributed uniformly in an entire flow field, and they are likely affected by many factors such as shear stress or temperature during their formation and may have different distributions at different conditions. In order to investigate the effect of surfactant additives on heat transfer at different flow regions, we need to establish a model which can consider the non-uniform distribution difference of surfactant additives. In [1] a simplified and ideal bilayer model with coexisting Newtonian and viscoelastic fluid was proposed to study the drag-reduction features by surfactant additives. In the present study, we employ the bilayer model to simulate the turbulent heat transfer of surfactant drag-reducing fluid flow and examine the effectiveness of surfactant additives to turbulent heat transfer at different flow regions.

2. Physical model

A bilayer model for flow with Newtonian and viscoelastic fluid coexistence was proposed in [1]. The flow to be studied was a fully-
87 Newtonian and viscoelastic motion, Flow A and Flow B as shown in Fig. 2, were studied, where developed channel flow as shown in Fig. 1, in [1] two types of fluid motion, Flow A and Flow B as shown in Fig. 2, were studied, where Newtonian and viscoelastic fluids separately flow at different layers with the interface parallel to the walls between them. In Flow A, the network structures exist at the center region of the channel, whereas in Flow B they exist at the near-wall region. Since similar conclusions can be drawn for Flow A and Flow B, in this study we consider only Flow A. Eight cases are considered with viscoelastic fluid thicknesses shown in Table 1. The first case in Table 1 is Newtonian fluid and the last case is complete viscoelastic fluid. As for the other six cases between the first and last case, Newtonian and viscoelastic fluids coexist. It should be pointed out that the shear stress and temperature dependent network structures evolve as time elapses, and the interface shape as showed in Fig. 2 may be irregular and variable in a real flow. For simplicity, the bilayer structures were proposed to model the complicated heterogeneous distributions of surfactant additives in the flow.

3. Governing equations and numerical methods
The turbulent drag-reducing channel flow with a constant heat flux qw imposed on both walls is shown in Fig. 1. The dimensionless governing equations for fully developed turbulent channel flow with heat transfer based on Giesekus model can be written as follows:

\[ \frac{\partial u_i}{\partial x_i} = 0 \]  

Continuity equation:

\[ \rho \frac{\partial u_i}{\partial t} + \partial \left( \rho u_i u_j \right)/\partial x_j = \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \mu_{ij}}{\partial x_j} \]  

Momentum equation:

\[ \rho \frac{\partial \tau_{ij}}{\partial t} + \partial \left( \rho \tau_{ij} u_j \right)/\partial x_j = \frac{\partial \mu_{ij}}{\partial x_j} - \frac{\partial \mu_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \]  

Energy equation:

\[ \frac{\partial q_{ij}}{\partial x_j} = \lambda \frac{\partial T}{\partial x_j} + \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} - \frac{\partial \tau_{ij}}{\partial x_j} \]  

Ensemble average over the spanwise direction and time

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Table 1

<table>
<thead>
<tr>
<th>Layer Type</th>
<th>U*</th>
<th>Re_m</th>
<th>C_1 (10^-3)</th>
<th>C_2^*(10^-3)</th>
<th>DR%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian</td>
<td>14.539</td>
<td>3680</td>
<td>9.333</td>
<td>9.386</td>
<td>-</td>
</tr>
<tr>
<td>VE (0.4)</td>
<td>15.076</td>
<td>3782</td>
<td>8.799</td>
<td>9.317</td>
<td>5.537</td>
</tr>
<tr>
<td>VE (0.5)</td>
<td>15.141</td>
<td>3756</td>
<td>8.724</td>
<td>9.307</td>
<td>6.260</td>
</tr>
<tr>
<td>VE (0.6)</td>
<td>16.519</td>
<td>3786</td>
<td>9.299</td>
<td>6.823</td>
<td></td>
</tr>
<tr>
<td>VE (0.7)</td>
<td>15.388</td>
<td>3893</td>
<td>9.277</td>
<td>8.361</td>
<td></td>
</tr>
<tr>
<td>VE (0.8)</td>
<td>16.385</td>
<td>4039</td>
<td>9.123</td>
<td>18.445</td>
<td></td>
</tr>
<tr>
<td>VE (0.9)</td>
<td>17.291</td>
<td>4323</td>
<td>6.690</td>
<td>9.003</td>
<td>25.694</td>
</tr>
<tr>
<td>VE (1.0)</td>
<td>18.076</td>
<td>4519</td>
<td>8.903</td>
<td>31.255</td>
<td></td>
</tr>
</tbody>
</table>

Giesekus constitutive equation:

\[
\frac{\partial \sigma_{ij}}{\partial t} + \frac{\partial (\sigma_{ij} + p) }{\partial x_j} = \frac{1}{Re_\tau} \frac{\partial}{\partial x_j} \left( \frac{2}{\eta} \frac{\partial \sigma_{ij}}{\partial x_j} \right) + \frac{\beta}{Re_\tau} \frac{\partial \sigma_{ij}}{\partial x_j} + \delta_{ii}
\]

Energy equation:

\[
\frac{\partial \theta}{\partial t} + \frac{\partial \left( U_x \theta \right) }{\partial x_j} = \frac{2 u^+}{C_1^*(10^{-3}) Re} \int_{-1}^{1} U_y dy' + \frac{1}{Re_\tau Pr} \frac{\partial}{\partial x_j} \left( \frac{\partial \theta}{\partial x_j} \right)
\]

It is seen that compared with Newtonian fluid in the momentum equation (Eq. (2)), there is an extra term associated with the interaction between the network structure and the solvent. In the Newtonian fluid region, the additional stress term is not included. Eq. (3) is the Giesekus constitutive equation to calculate the conformation tensor of the network structure.

Calculations were performed with parameters \(Re_\tau = 125\), \(We_\tau = 25\), \(\alpha = 0.001\), \(\beta = 0.1\) and \(Pr = 0.71\) in the viscoelastic fluid region and \(Re_\tau = 125\) and \(Pr = 0.71\) in the Newtonian fluid region. It is known that the smallest scale in temperature fluctuation decreases with the increase of Prandtl number (exactly speaking, the smallest degree in temperature fluctuation varies in a manner inversely proportional to \(Pr^{1/2}\)). At a first step, the change of the turbulent characteristics engendered by the viscoelasticity was investigated. In order to overcome thermal-resolution barrier by relatively large Prandtl number of water, Prandtl number was set to 0.71. A computational box of \(10 h \times 2 h \times 5 h\) in the \(x, y\) and \(z\) directions was chosen for simulation and the computational domain in wall units was \(1250 \times 250 \times 625\). A grid system of \(64 \times 64 \times 64\) in \(x, y\) and \(z\) meshes was adopted. In addition, grid validation was given in Fig. 3, which shows the mean velocity profile and mean temperature profile.
Table 2
Results of heat transfer reduction (VE (δ) means the thickness of viscoelastic flow layer is δ).

<table>
<thead>
<tr>
<th>VE (δ)</th>
<th>Θ_m</th>
<th>Nu</th>
<th>Nu^k</th>
<th>HTR%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian VE (0)</td>
<td>13.499</td>
<td>13.149</td>
<td>13.147</td>
<td>–</td>
</tr>
<tr>
<td>VE (0.4)</td>
<td>14.139</td>
<td>12.553</td>
<td>13.460</td>
<td>6.732</td>
</tr>
<tr>
<td>VE (0.5)</td>
<td>14.258</td>
<td>12.449</td>
<td>13.506</td>
<td>7.828</td>
</tr>
<tr>
<td>VE (0.6)</td>
<td>14.303</td>
<td>12.410</td>
<td>13.543</td>
<td>8.367</td>
</tr>
<tr>
<td>VE (0.7)</td>
<td>14.484</td>
<td>12.255</td>
<td>13.647</td>
<td>10.195</td>
</tr>
<tr>
<td>VE (0.8)</td>
<td>15.332</td>
<td>11.577</td>
<td>14.394</td>
<td>19.569</td>
</tr>
<tr>
<td>VE (0.9)</td>
<td>16.315</td>
<td>10.879</td>
<td>15.019</td>
<td>27.565</td>
</tr>
<tr>
<td>VE (1.0)</td>
<td>17.666</td>
<td>10.047</td>
<td>15.563</td>
<td>35.440</td>
</tr>
</tbody>
</table>

profile in two sets of grids: 64 × 96 × 64 grids and 64 × 64 × 64 grids for Newtonian flow and viscoelastic flow respectively. It can be seen that the profiles in different grid systems agree with each other very well.

Non-uniform grids in the wall-normal direction were used with grids clustered in the near-wall region and at the interface region. Grid-spacing Δy^+ increased progressively from around 0.3 near the wall to 6 in the center. Uniform grids were used in the x and z directions and the corresponding grid-spacings were Δx^+ = 19.53 and Δz^+ = 9.77 respectively. The periodic boundary conditions were imposed in both the streamwise (x) and spanwise (z) directions, while the nonslip condition was adopted for the top and bottom walls. The numerical method used here was a fractional-step method. A dimensionless time-step 2 × 10^{-4} was used. The Adams–Bashforth scheme was used for time-advancement and a fourth order central compact difference scheme is applied to discretize the convective and diffusion terms whereas MINMOD scheme [9] is used to discretize the convective terms in the Giesekus constitutive equations to enhance numerical stability. The grid and time-step resolution used in the present study was proved adequate in former study.[9] At the interface of the Newtonian and viscoelastic fluid regions, the following shear stress and normal stress balance equations were satisfied:

\[
\frac{\partial \tau}{\partial y^+} = \frac{\partial \tau}{\partial y^+}_{\text{VE}} + \beta \text{Re}_c \text{C}_{16}/\text{We}_c
\]

\[
\frac{\partial \tau}{\partial y^+} = \frac{\partial \tau}{\partial y^+}_{\text{VE}} + \beta \text{Re}_c \left( \text{C}_{17} - 1 \right) / \text{We}_c
\]

\[
\frac{\partial \tau}{\partial y^+} = \frac{\partial \tau}{\partial y^+}_{\text{VE}} + \beta \text{Re}_c \text{C}_{18}/\text{We}_c
\]

\[
\frac{\partial \tau}{\partial y^+} = \frac{\partial \tau}{\partial y^+}_{\text{VE}} + \beta \text{Re}_c \text{C}_{19}/\text{We}_c
\]

4. Results and discussion
Drag-reduction rate is defined as the reduction of friction factor for Newtonian fluid at equal mean Reynolds number \( Re_m \).

\[ DR\% = \left( \frac{C_f^D - C_f}{C_f^D} \right) \times 100\% \]  

\[ C_f^D \] was evaluated by Dean's equation \( C_f^D = 0.073 Re_m^{-0.25} \) [Dean,1978] [10]. Table 1 shows the calculated frictional factor \( C_f \) evaluated frictional factor \( C_f^D \) and drag-reduction rate. It is observed that for Newtonian fluid, the calculated frictional factor agrees quite well with Dean's correlation. However, for the others cases, with increase of viscoelastic region, the calculated frictional factor decreases, meanwhile, the drag-reduction rate becomes higher.

The heat transfer reduction HTR% is defined as the reduction of Nusselt number for the Newtonian fluid at the same mean Reynolds number \( Re_m \).

\[ HTR\% = \left( \frac{Nu^k - Nu}{Nu^k} \right) \times 100\% \]  

\( Nu^k \) was calculated by Kays and Crawford's equation \( Nu^k = 0.022 Re_m^{0.8} Pr_{fl}^{0.5} \) [Kays,1980] [11]. Table 2 shows the calculated Nusselt number \( Nu \) and heat transfer reduction rate. It is evident that for Newtonian fluid, the calculated Nusselt number agrees quite well with Kays and Crawford's equation.

As Tables 1 and 2 indicate, mean velocity, mean Reynolds number and DR% increase but the frictional factor decreases as the thickness of
viscoelastic flow layer increases; at the same time, mean temperature and HTRs also increase but the Nusselt number decreases. By comparing HTRs and DRs, we can find that as drag reduction rate increases, the heat transfer is weakened seriously; furthermore, the heat transfer reduction rate is greater than the drag reduction rate in all the cases of drag-reducing flow. The finding is in coincidence with the experiment by Li et al. (2004) [5].

The local contribution to the drag reduction rate and the heat transfer reduction rate shown in Figs. 4 and 5 are respectively defined by:

\[
\text{Contribution rate to DR}_{\gamma(y)} = \frac{DR_{\gamma(y)} - DR_{\gamma|0.1}}{DR_{\gamma|0.1}}
\]

\[
\text{Contribution rate to HTR}_{\gamma(y)} = \frac{HTR_{\gamma(y)} - HTR_{\gamma|0.1}}{HTR_{\gamma|0.1}}
\]

It is clear that the network structure plays an important role in the vicinity of walls (0.7 ≤ \(y^*\) ≤ 1) in these two figures. In these near-wall regions, the effectiveness induced by surfactant additives to drag reduction and heat transfer reduction is much more obvious than that in the center region. Especially at 0.7 ≤ \(y^*\) ≤ 0.8 layer, the contribution rate to drag reduction generated by surfactant additives is more than 30% while that to heat transfer reduction is more than 25%; they are the greatest reduction rates in all layers. The layer 0.8 ≤ \(y^*\) ≤ 0.9 is the second most effective region for network structure, and the contribution rates to drag reduction and heat transfer reduction in this layer reach 23% and 22% respectively. However, at the layer of 0.9 ≤ \(y^*\) ≤ 1, the closest layer to the wall, the contribution rate to drag reduction is no more than 18% but to heat transfer reduction is still as high as 22%. It can be seen from analysis above that the network structure produces a more significant effectiveness to heat transfer than that to drag reduction in the regions next to the wall. From these two figures, it also can be seen that the local contribution rates to drag reduction and heat transfer reduction at the center bulk flow region 0 ≤ \(y^*\) ≤ 0.7 are much less than that in the vicinity of walls, which agrees with the previous study quite well [1]. In short, all the results in Figs. 4 and 5 indicate that surfactant additives perform more effectively at the buffer layer.

Fig. 6 shows the mean velocity distributions in wall unit logarithmic coordinates. It is clear that the mean velocity of drag-reducing flow is higher than that of Newtonian flow, and the mean velocity increases as the viscoelastic flow layer thickness increases. Furthermore, the increasing scale of mean velocity is proportional to the local contribution rate to DRs. For VE(0.4~0.6) mean velocity is slightly greater than that of Newtonian flow. When it comes up to VE(0.7~1.0), the mean velocity increases quickly as the thickness of viscoelastic flow layer extends. The greatest increment of mean velocity appears between VE(0.7) and VE(0.8), and the second greatest increment locates between VE(0.8) and VE(0.9). This phenomenon agrees well with Fig. 4 illustrating that the vast majority of local contribution rate to DRs is within the flow layers 0.7 ≤ \(y^*\) ≤ 0.9. All the analyses above confirm again that the buffer layer is the most effective region for surfactant additives to exert drag reduction and heat transfer reduction in turbulent heat transfer channel flow.

The root-mean-squares of velocity fluctuation in streamwise, wall-normal and spanwise direction are respectively shown in Figs. 7~9. As \(\delta\) increases, streamwise velocity fluctuation grows and its peak value increases; at the same time, mean temperature and HTRs also increase but the Nusselt number decreases. By comparing HTRs and DRs, we can find that as drag reduction rate increases, the heat transfer is weakened seriously; furthermore, the heat transfer reduction rate is greater than the drag reduction rate in all the cases of drag-reducing flow. The finding is in coincidence with the experiment by Li et al. (2004) [5].

The local contribution to the drag reduction rate and the heat transfer reduction rate shown in Figs. 4 and 5 are respectively defined by:

\[
\text{Contribution rate to DR}_{\gamma(y)} = \frac{DR_{\gamma(y)} - DR_{\gamma|0.1}}{DR_{\gamma|0.1}}
\]

\[
\text{Contribution rate to HTR}_{\gamma(y)} = \frac{HTR_{\gamma(y)} - HTR_{\gamma|0.1}}{HTR_{\gamma|0.1}}
\]
The peak values of temperature increases. For drag-reducing between Newtonian and drag-reducing. Fig. 11 shows the temperature velocity profile. In addition, it is found that there are many similarities between Newtonian and drag-reducing flow are in coincidence with the linear relationship $\Theta^+ = Pr \times y^+$. The mean temperature distribution of all the cases in wall unit logarithmic coordinates is shown in Fig. 10. By comparison with the mean temperature of Newtonian fluid flow, the mean temperature of drag-reducing flow is greater, and ascends as $\delta$ increases. As presented in Fig. 10, all the mean temperature profiles of Newtonian flow and drag-reducing are shifted toward the bulk flow region. This indicates that velocity profile and temperature profile.

Fig. 11 shows the temperature fluctuation in all cases. Comparison between Newtonian and drag-reducing flow shows the temperature fluctuation ascends as the thickness of viscoelastic flow layer increases. For drag-reducing flow, the peak value of temperature fluctuation shifts to the bulk flow region. The thicker the viscoelastic flow layer is, the nearer the peak value locates to the bulk flow region. The peak values of temperature fluctuation are much nearer to the bulk flow region than that of streamwise velocity fluctuation. Taking VE (1.0) for example, the peak value of streamwise velocity fluctuation is at about $y^+ = 20$ while that of temperature fluctuation locates at $y^+ = 25$. It also supports that the network structure exerts a greater influence on heat transfer reduction than that on drag reduction.

The streamwise turbulent heat flux $u' \theta^{+}$ is shown in Fig. 12. It is obvious that the streamwise turbulent heat flux of drag-reducing flow is much greater than that of Newtonian flow and its peak value shifted toward the bulk flow region, especially for VE (0.8–1.0).

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significant increase of the streamwise turbulent heat flux is primarily caused by both the increase of the streamwise velocity fluctuation and the increase of the temperature fluctuation. And another reason is the close correlation between streamwise velocity and temperature of drag-reducing flow, which is confirmed in previous study [6].

Fig. 13 shows the wall-normal turbulent heat flux $-\nu^+ \theta^+$ in all cases. With the increase in thickness of viscoelastic flow layer, the wall-normal turbulent heat flux reduces and its peak value shifts to the bulk flow region. For this reason, heat transfer in wall-normal direction is depressed so dramatically that the heat transfer reduction rate rises up rapidly. Just as the decrease of the Reynolds stress leads to drag reduction [12], depression of wall-normal turbulent heat flux also plays a very important role in heat transfer reduction.

Fig. 14 shows the distribution of conductive heat flux. As $\delta$ increases, conductive heat flux is enhanced, especially in the buffer layer. Its increase compensates for the decrease of wall-normal turbulent heat flux and ensures the total heat flux equation to be satisfied.

Fig. 16. Instantaneous speed streaks and thermal streaks on the $x-z$ plane locate at $y^+ = 15$. (a1) Newtonian speed streak. (a2) Newtonian thermal streak. (b1) VE (0.5) speed streak. (b2) VE (0.5) thermal streak. (c1) VE (0.8) speed streak. (c2) VE (0.8) thermal streak. (d1) VE (1.0) speed streak. (d2) VE (1.0) thermal streak.
The total heat flux can be deduced from the averaged energy equation:

\[ q_{\text{total}} = 1 - \int_0^1 U^+ d y^+ = \frac{1}{\Pr} \int_0^1 \frac{\partial \theta^+}{\partial y^+} - \nu^+ \theta^+ d y^+ \]  

(12)

The budgets of heat flux of VE(0) and VE(0.9) are shown in Fig. 15. The instantaneous velocity streaks and thermal streaks on the \( x - z \) plane located at \( y^+ = 15 \) are compared in Fig. 16. It is seen that there is a correlation between thermal streak and velocity streak: while high-thermal streaks are associated with high-velocity streaks, low-thermal streaks are associated with low-velocity streaks. The width of thermal streak and velocity streak of drag-reducing fluid is larger than that of Newtonian fluid. As to drag-reducing flow, as the thickness of viscoelastic flow layer increases, velocity and thermal streaks become wider and wider. It is indicated that there is a similarity in the mechanism of drag reduction and heat transfer reduction induced by surfactant additives.

5. Conclusions

A bilayer model is employed to study the heat transfer reduction mechanism of surfactant drag-reducing flow with a constant heat flux imposed on both the walls with DNS analysis. The effectiveness induced by surfactant additives to drag reduction and heat transfer reduction at different flow regions is calculated quantitatively. Some important statistics and parameters were obtained, such as DR\%, HTR\%, Nusselt number, mean temperature, root-mean square of temperature fluctuation and turbulent heat flux. Based on these examinations, the relationship between drag reduction and heat transfer reduction was discussed and analyzed. Some conclusions are achieved as follows:

1. According to calculation results in the study (at parameters of \( Re_x = 125, Pr = 0.71 \)), the heat transfer reduction rate is greater than drag reduction rate for all drag-reducing flows. It indicates that the network structure exerts a greater influence on heat transfer than that on drag reduction.

2. With the thickness of the viscoelastic flow layer increases, the mean velocity and mean temperature profiles shift upwards in logarithmic region, and the drag reduction rate and heat transfer reduction rate become higher.

3. The quantitative calculation results of effectiveness on different cases show that the network structure induced by surfactant additives plays an important role in drag reduction and heat transfer at the buffer layer, and it imposes more effect on heat transfer reduction than that on drag reduction, especially in the layer next to the wall (\( 0.9 \leq y^+ \leq 1 \)).

4. As streamwise turbulent heat flux of drag-reducing flow dramatically increases, the peak value shifts toward the bulk flow region, which indicates that there is a close correlation between streamwise velocity and temperature.

5. Due to the strong depression on the wall-normal velocity fluctuation in viscoelastic flow, the wall-normal turbulent heat flux decreases as viscoelastic flow layer expands. This is identified as a primary reason for heat transfer reduction.

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