Effect of parameters of traveling wave-like blowing and suction on skin-friction drag reduction and heat transfer enhancement in turbulent channel flow

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ABSTRACT

Direct numerical simulations of turbulent channel flows controlled by the traveling wave-like blowing and suction are performed. We focus on simultaneous achievement of skin-friction drag reduction and heat transfer enhancement due to the control. The control performance is parametrically investigated. Three different thermal boundary condition are examined: constant temperature difference, heat flux, and heat generation conditions. The dissimilar control effects, i.e., the heat transfer enhancement and the drag reduction, are obtained when the wave travels in the upstream direction.

INTRODUCTION

Flow control to decrease skin-friction drag in turbulent flows is of importance in mitigating environmental impact and many control techniques are examined numerically and experimentally. In addition, the heat transfer enhancement is also important in heat transfer devices, while simultaneous achievement of drag reduction and heat transfer enhancement (i.e., dissimilar control) is usually difficult due to strong analogy between momentum and heat transfer.

In order to obtain the dissimilar control effect, Higashi *et al.* (2010) employed the traveling wave-like blowing and suction from the wall in the laminar channel flow. Their analysis showed that the dissimilar control effect can be obtained when the wave travels in the upstream direction (i.e., opposite direction to the base flow). It is also known that the upstream traveling wave destabilizes the flow and the downstream traveling wave stabilizes the flow (Lieu *et al.*, 2010; Moarref & Jovanović, 2010; Nakanishi *et al.*, 2012; Mamori *et al.*, 2014). Very recently, Uchino *et al.* (2017) made the DNS of the turbulent channel flow controlled by the traveling wave-like wall deformation to investigate the heat transfer performance. They confirmed that 13 % enhancement of the heat transfer by the upstream traveling wave with the large amplitude and the short deformation period.

In this study, we perform direct numerical simulations of the turbulent channel flows controlled by the traveling wave-like blowing and suction and investigate the drag reduction and heat transfer performance. This study is the extension of Higashi *et al.* (2010): the parametric study is conducted to show the effect of the parameter on the control performance; we compare three different thermal boundary conditions.

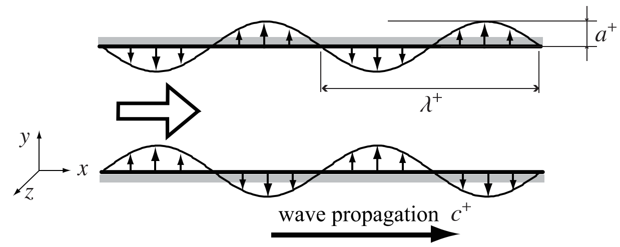

Figure 1. Traveling wave-like blowing and suction from walls in the channel flow.

Numerical Simulation

We perform the DNS of the turbulent channel flow controlled by the traveling wave-like blowing and suction from the wall. The governing equations are continuity, Navier-Stokes, and energy equations, i.e.,

$$\frac{\partial u_i}{\partial x_i} = 0, \tag{1}$$

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_k u_i}{\partial x_k} = -\frac{\partial P}{\partial x} - \frac{\partial p}{\partial x_i} + \frac{1}{\mathrm{Re}_\tau}\frac{\partial^2 u_i}{\partial x_k \partial x_k}, \tag{2}$$

$$\frac{\partial T}{\partial t} + \frac{\partial u_k T}{\partial x_k} = Q + \frac{1}{\mathrm{Re}_\tau \mathrm{Pr}}\frac{\partial^2 T}{\partial x_k \partial x_k}. \tag{3}$$

Here, u_i denotes the velocity in the x_i direction; T is the temperature; t is the time; p is the pressure. The friction Reynolds number Re_τ is defined by the friction velocity u_τ^* and the channel half-width δ^*. The superscript of the asterisk indicates the dimensional variable. In this study, the streamwise, wall-normal, and spanwise directions are denoted x, y, and z and the corresponding velocities are u, v, and w, respectively (for notational convenience, x_i and u_i (for $i = 1...3$) are used interchangeably).

Figure 1 shows schematic of the channel flow. The computational domain is set to be $L_x \times L_y \times L_z = 4\pi \times 2 \times 3.5$ and the corresponding number of grid points is $N_x \times N_y \times N_z = 256 \times 96 \times 128$ or $N_x \times N_y \times N_z = 256 \times 288 \times 128$. The finer mesh is used to evaluate flow statistics. The periodic boundary condition is imposed in homogeneous direction and the traveling wave-like blowing and suction is imposed on the walls, as

$$u_w = 0, \ \ v_{w\pm} = \pm a \cos\left(\frac{2\pi}{\lambda}(x - ct)\right). \tag{4}$$

This is the varicose mode. The superscripts of $w+$ and $w-$ indicate the upper and lower walls, respectively. The control parameters are amplitude of the wave a, the wavelength λ, and the wavespeed c. In this study, we make parametric study for a, λ, and c: 96 cases are conducted in total.

All simulations start from an uncontrolled fully developed channel flow of $\mathrm{Re}_\tau = 180$. The mean pressure gradient in the

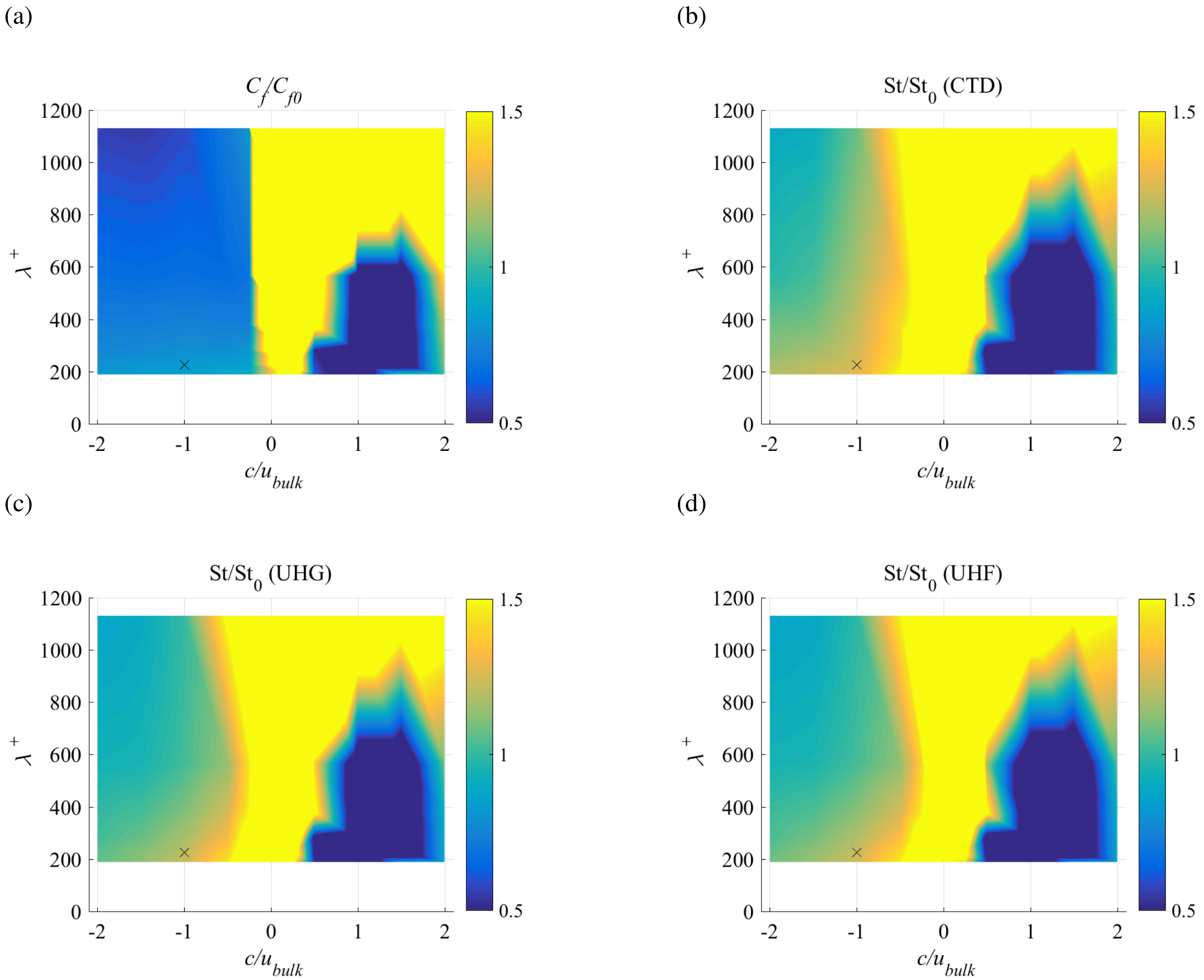

Figure 2. Map of the normalized skin-friction drag coefficient and Stanton number as a function of wavespeed and wavelength. The cross represents a reference case. The amplitude is set to be $a/u_{\text{bulk}} = 0.1$.

streamwise direction is kept constant, $-\partial P/\partial x = 1.0$ and the drag reduction corresponds to the increase of the bulk flow rate. The skin-friction Reynolds number $\text{Re}_\tau = 180$ corresponds to the bulk Reynolds number of $\text{Re}_b = 5600$ in the uncontrolled flow. The Prandlt number is set to be $\text{Pr} = 1.0$. The heat source is denoted by Q and we examined three different boundary conditions as (Kawamura *et al.*, 2000):

$$\begin{aligned} &\text{CTD}, \;\; T_{w-} = 0.0, \;\; T_{w+} = 2.0, \;\; Q = 0.0; \\ &\text{UHF}, \;\; T_{w-} = 0.0, \;\; T_{w+} = 0.0, \;\; Q = u/u_b; \\ &\text{UHG}, \;\; T_{w-} = 0.0, \;\; T_{w+} = 0.0, \;\; Q = 1.0. \end{aligned} \tag{5}$$

The CTD, UHF, and UHG means “constant temperature difference”, “uniform heat flux”, and “uniform heat generation”, respectively. We impose $Q = 1.0$ in the UHG case so that the Navier-Stokes and energy equations are similar.

The cost function are the skin-friction coefficient c_f and the Stanton number St, as

$$c_f = \frac{\tau_w^*}{\frac{1}{2}\rho^* u_b^{*2}}, \;\; \text{St} = \frac{q_w^*}{\rho^* c_p^* u_b^* T_b^*} \tag{6}$$

Here, τ_w^* is the wall shear stress, ρ^* is the density of the fluid, u_b^* is the bulk mean velocity, q_w^* is the heat flux on the wall, c_p^* is the specific heat, T_b^* is the bulk mean temperature.

Results

Figure 2 shows results of the parametric study on the skin-friction drag reduction and the heat transfer enhancement. Here, the skin-friction coefficient c_f and the Stanton number St are normalized by those of the uncontrolled flow. In the upstream traveling wave case ($c < u_{bulk}$), the skin-friction drag decreases below the uncontrolled case. In the downstream traveling wave case ($c > u_{bulk}$), relaminarization phenomena appear at $\lambda^+ < 700$ and the skin-friction increases (c_f/c_{f0}) in the other parameter set. Here, the superscript of the plus shows the wall unit. The Stanton number distribution is similar to that of c_f: St/St_0 is larger than one for the upstream traveling wave ($c/u_{bulk} < 0$). In addition, the major difference among different thermal boundary condition is not observed. In the following, we chose parameter set of $c/u_{bulk} = -1.0$ and $\lambda^+ = 226$ as a reference case (denoted by the cross in Fig. 2). This case is one of the parameter sets which induce the skin-friction drag reduction and the heat transfer enhancement simultaneously e.g., $c_f/c_{f0} = 0.90$ and $\text{St}/\text{St}_0 = 1.24$ in the UHG case. According to Uchino *et al.* (2017), in the wall deformation wave case, both the skin-friction drag and heat transfer increase and the analogy factor is larger than unity at the CTD case. For example, the analogy factor of 1.03 is obtained at $a/2u_{\text{bulk}} = 0.1$, $c/2u_{\text{bulk}} = -3$, and $\lambda^+ = 1130$. However, no improvement in the analogy factor was confirmed at the UHG case. This is likely due to the difference between the wall-deformation and blowing and suction.

Figure 3 shows the Reynolds shear stress (RSS) and the turbu-

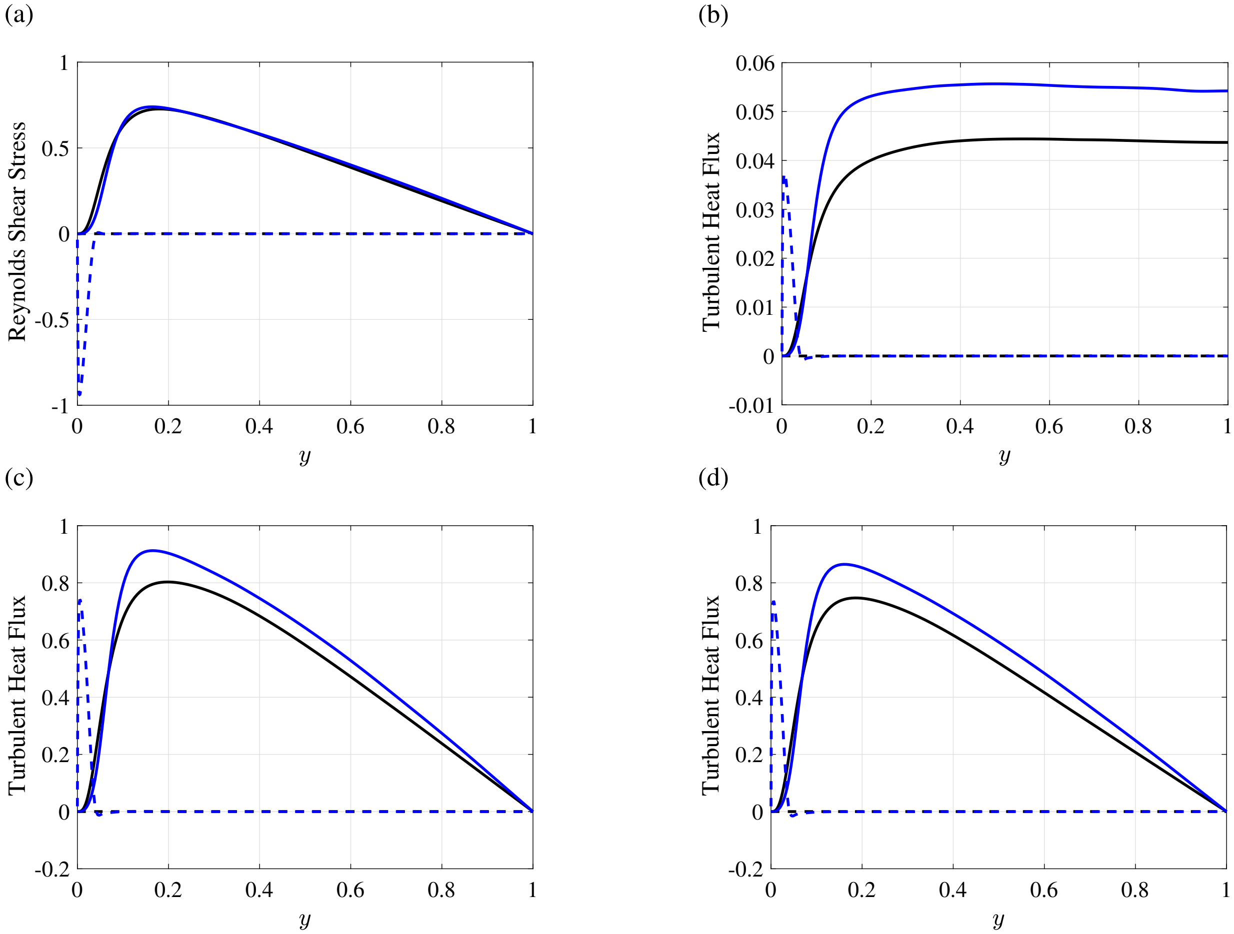

Figure 3. Profile of (a) the RSS, (b) the THF in the CTD case, (c) the THF in the UHG case, and (d) the THF in the UHF case. The solid and broken lines are the random and periodic components, respectively. The black and blue lines are the uncontrolled and the reference cases, respectively.

lent heat flux (THF). Since the present control input has a periodicity in the streamwise direction, we decomposed them into the random and periodic component: the random component corresponds likely to the activity of the streamwise vortical structure; the periodic component corresponds to the spanwise roller-like vortical structure (Mamori & Fukagata, 2014). As well known, the RSS and the THF play an important role for the increase or decrease of c_f and St (Fukagata *et al.*, 2002; Kasagi *et al.*, 2010). As shown in Fig. 3(a), the random RSS is slightly smaller than that of the uncontrolled case in the region near the wall, whereas it is slightly larger than that away from the wall. Additionally, the negative periodic-RSS appears in the region very close to the wall. Since the turbulent contribution to the skin-friction drag equals the integration of the y-weighted RSS, the negative periodic-RSS is responsible to the reduction of the skin-friction drag. This negative RSS is due to the spanwise roller-like vortical structure generated by the traveling wave (Mamori *et al.*, 2014). Figure 3(b) shows the THF in the CTD condition. The random-THF in the controlled case is slightly smaller than that of uncontrolled case in the region very close to the wall, whereas it enhances away from the wall. And, the positive periodic-THF appears in the near wall region. The positive-THF contributes the heat transfer enhancement. The similar trend is observed in the UHG and UHF cases as shown in Figs. 3(c-d).

Figures 4 and 5 display the spatial distribution of the RSS and THF. The double prime means random components and the tilde means periodic component. The periodic component of statistics are obtained in a "moving frame" which moves with the same speed of the traveling wave. The component is denoted by the angle bracket. Figure 4 shows that the distribution of the random-RSS and random-THF are affected by the traveling wave: these are very small in the region near the wall and enhanced away from the wall. The periodic components, in contrast, the positive and negative values are observed alternatively. In the region very close to the wall, the negative periodic-RSS area is larger than the positive area whereas the positive periodic-THF area is larger than the negative area. It results in the negative periodic-RSS and positive periodic-THF close to the wall as shown in Fig. 3. Accordingly, the simultaneous achievement of the skin-friction drag reduction and the heat transfer enhancement is obtained by the the upstream traveling wave-like blowing and suction.

Conclusion

We performed the DNS of the turbulent channel flow controlled by the traveling wave-like blowing and suction. The parametric study is conducted to investigate the range of the simultaneous achievement for the skin-friction drag reduction and heat transfer enhancement. The effect of the difference among the thermal boundary conditions on the heat transfer performance is small. The simultaneous achievement of the heat transfer enhancement and the drag reduction is obtained in the upstream traveling wave case, since the negative RSS and positive THF appear in the region near the wall.

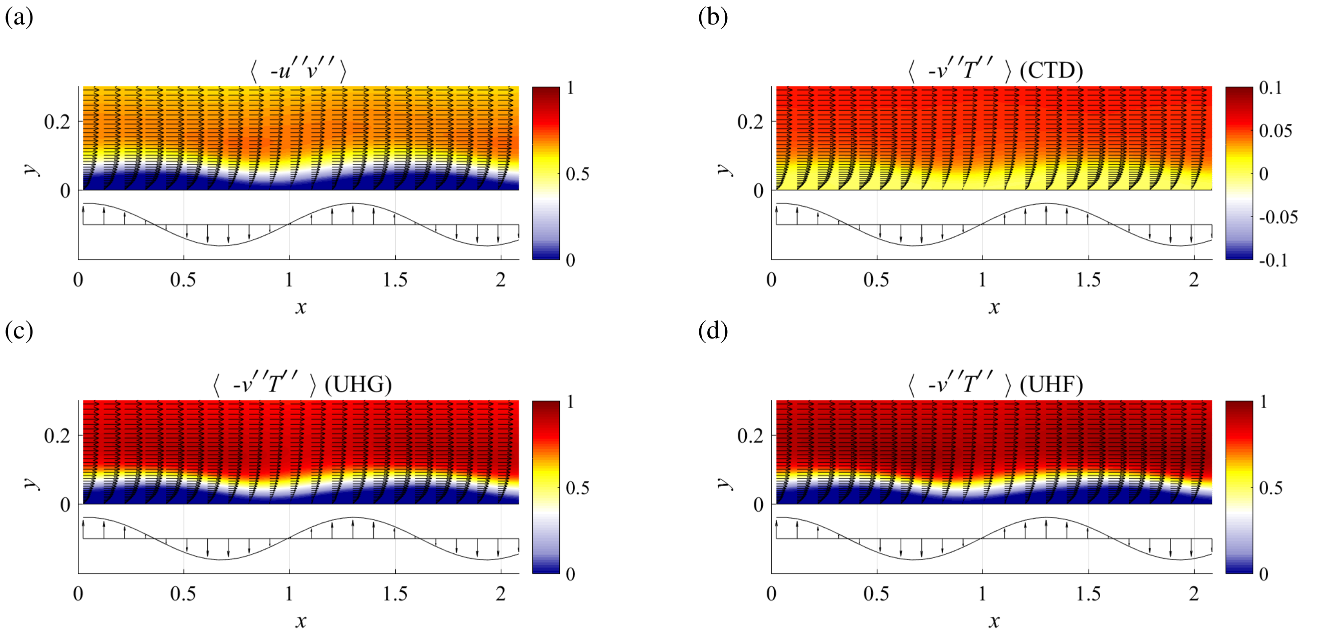

Figure 4. Distribution of the random-RSS and THF in the region near the wall, together with the blowing and suction from the wall.

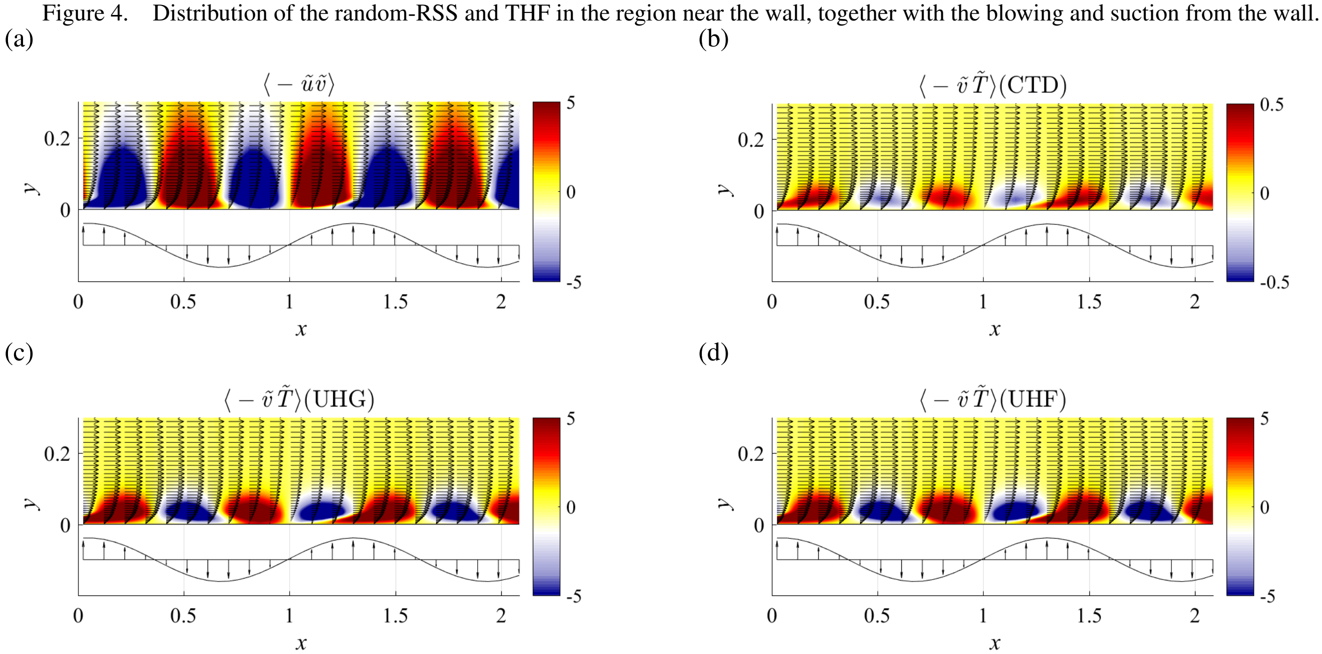

Figure 5. Distribution of the periodic-RSS and THF in the region near the wall, together with the blowing and suction from the wall.

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