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Research Article
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Exhaust process of cryogenic nitrogen gas from a cryogenic wind tunnel with an inclined exit

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Abstract: A new structural design for the vent stack with an inclined exit was proposed to reduce the settlement hazard of the cryogenic plume from a cryogenic wind tunnel; it extends the plume trajectory to increase the effective contact space and time for mixing between the plume gas and atmospheric air before the plume settles to the ground, contributing to more efficient energy consumption for heating. Reduced-scale experiments and numerical simulations of plume dispersion based on vertical and 30°- and 45°-inclined exits were conducted to study harm reduction and energy-saving potential. Analyses of the minimum temperature and minimum oxygen concentration of the plume near the ground indicate that the new exhaust design with an inclined exit clearly reduces the settlement hazard. Under windless conditions and without using a fan-ejector system, up to 15.9% of the heating energy used by the burner can be saved by adopting the new design.

Key words: Cryogenic gas dispersion; Cryogenic wind tunnel; Exhaust method; Hazard reduction; Inclined exit

1 Introduction

A cryogenic wind tunnel is a large, sophisticated aerodynamics ground-test facility necessary for the research and development of large and high-speed aircraft (Green and Quest, 2011). As air density is much higher at cryogenic temperatures compared to that in room-temperature wind tunnels, cryogenic wind tunnels can achieve a higher Reynolds number while maintaining low energy consumption (Goodyer and Kilgore, 1972; Kilgore et al., 1974; Kilgore and Dress, 1984; Smelt, 1991; Kilgore, 1994). To maintain a cryogenic environment, a steady stream of liquid nitrogen spray from nozzles at the front of a drive fan vaporizes rapidly to form cryogenic nitrogen gas, which absorbs the heat generated by the fan. Taking the US National Transonic Facility (NTF) as an example, its large-scale cryogenic engineering system can inject liquid nitrogen at rates up to 450 kg/s to keep steady thermodynamic conditions for testing (Kilgore, 2005). This leads to a large quantity of nitrogen gas being discharged into the environment. To avoid posing potential hazards to the public, such as frostbite damage or oxygen deficiency due to cryogenic dense gas gravity settlement, the question of how to ensure the safety of cryogenic wind-tunnel exhaust must be considered in the design and operation of cryogenic wind tunnels.

Unlike cryogenic fluid leakage and dispersion caused by storage-vessel or pipeline damage, the dispersion process of cryogenic wind tunnel exhaust is artificially operated and controlled. By considering both operating and environmental conditions, the operators of a cryogenic wind tunnel can take pre-treatment measures to reduce hazards from the cryogenic exhaust plume. The National Aeronautics and Space Administration (NASA) conducted systematic research on the exhaust system decades ago to reduce hazard levels (Kilgore, 1976; Ivey, 1979; Bruce et al., 1984). The most basic and primitive approach is to discharge the cryogenic nitrogen exhaust through a high vent stack to increase the initial dispersion height (Ivey, 1979). At the US NTF, the cryogenic nitrogen gas is discharged from the top of a vent stack which is 3.35 m in diameter and 36.6 m in height (Lassiter, 1987).

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NASA developed a two-stage analytical model to simulate the process of cryogenic plume dispersion (Lassiter, 1987). In simulation results from a two-stage analytical model, the relative errors for centerline maximum height and distance downwind of the centerline at maximum height were 10.2%–13.4% and 52.9%–101.8%, respectively. The accuracy of NASA's two-stage analytical model still needs to be improved, however. In our previous work, we developed a numerical model with a modified Hertz-Knudsen relation which took into account the phase-change physics of the small quantity of water involved (Zhang et al., 2015). The relative errors of the two key parameters above were 1.3%–6.7% and 9.3%–30.2%, respectively, in the simulation results from this model, showing that the model's predictions were more consistent with the US NTF's experimental data than those of NASA's two-stage analytical model (Li et al., 2018). Alongside the model we developed, we performed a parametric sensitivity study on plume dispersion of the exhaust from a 0.3-m cryogenic wind tunnel. As the wind speed increases, the heat and mass transfer between the plume and atmospheric air was more adequate, and more cryogenic nitrogen gas was diluted by atmospheric-air mixing.

The additional measures adopted by NASA at the US NTF to safely discharge cryogenic nitrogen gas with no adverse effects on human, animal, or plant life include motor-driven fans, ejector mixers, and natural gas burners (Kilgore, 2005). The fan-ejector system is employed to mix atmospheric air with the cryogenic nitrogen gas such that the mixture is delivered to the exit of the vent stack at a sufficient elevation, and with the appropriate mixture ratio and momentum, to ensure proper dispersal of the negatively buoyant plume. To complement the system, natural gas burners are used to prevent any cold exhaust from falling to the ground while the heat provided by the induced atmospheric air is insufficient.

To reduce the energy consumption of such an exhaust system, process optimization has also been a concern for researchers. Some researchers have suggested that recovery of some of the energy from the tunnel exhaust is an attractive idea for saving energy and reducing the hazard of the cryogenic exhaust plume. Unfortunately, there are no specific options available to date because of the intermittent operation of all such wind tunnels (Kilgore, 2005).

Based on the operation and environmental conditions, a combination of ejectors, fans, and burners can effectively reduce the hazard of the cryogenic plume. As structural components which do not consume energy, ejectors are routinely used. Fans are used as regular supplements to the ejectors, while burners are used as a last resort in more severe cases. Although fans and burners have become standard components of cryogenic wind-tunnel exhaust systems, their significant energy consumption is still worth addressing. Structural improvements similar to the ejectors are of great significance for reducing the overall energy consumption of exhaust systems.

In this study, we tested a new structural design for the vent stack of a cryogenic wind tunnel with an inclined exit. Experimental study and numerical simulation were carried out to verify the advantages of the inclined-exhaust method over the traditional vertical-exhaust method in terms of hazard reduction. Furthermore, using the 0.3-m cryogenic wind tunnel in Southwest China (Li et al., 2018) as a reference, we were able to preliminarily estimate the energy-saving potential.

2 Experimental methodology

2.1 Exhaust method with inclined exit

The cryogenic exhaust in the design proposed here is discharged at sufficient height with the vent stack, and then continuous dilution is achieved through heat and mass transfer during mixing with atmospheric air. As the moving distance of the cryogenic gas increases, its temperature and components become more similar to those of the atmospheric air. In other words, along the plume trajectory, the further away from the exhaust source, the more harmless the plume is. For gases that exhibit gravity settlement, extending the settlement trajectory can reduce potential harm to the public. The most conventional method is to increase the initial height of the exhaust, although this results in greater flow resistance and increases manufacturing cost. In the new exhaust method with an inclined exit proposed here, the effect of extending the plume trajectory can be obtained by simple structural improvement.

As shown in Fig. 1a, the vent stack of the conventional cryogenic tunnel is vertical, and the initial

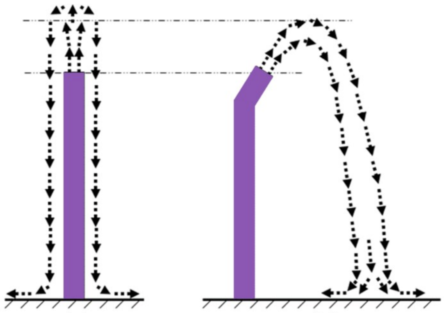

Fig. 1 Plume trajectories with a conventional exit (a) and inclined exit (b)

direction of the cryogenic nitrogen gas flow from the exit is vertical and upward. Assuming that the wind speed is zero, the trajectory of the cryogenic plume from the conventional vent stack is first vertical up and then vertical down. Fig. 1b shows that if the exit of the vent stack is inclined, the initial direction of the cryogenic nitrogen gas flow will also be inclined upward. With an inclined exit and the same initial height, the vertical velocity component decreases due to the horizontal component of the initial velocity, and the maximum height of the cryogenic plume is lower than that in the conventional exhaust method with a vertical exit. On the other hand, the horizontal velocity component gives the plume a horizontal movement trend, which makes its trajectory extended and approximately parabolic. Fig. 2 presents a simple example, in which the height of both exits is 20 m and the diameter is 1 m, but the exit in case a is conventional vertical while the one in case b is 30° inclined. The initial temperature of the exhausted cryogenic nitrogen gas was 110 K in both cases, and the initial velocity was 5 m/s. The centerline lengths of the plume profiles were measured with the professional image-analysis software ImageJ. The centerline length of the plume profile with the conventional exit (a) was 169.005 units, and with the 30° inclined exit (b) was 192.679 units. The extended trajectory means that the heat and mass transfer between the gas group in the plume and the atmospheric air can be more effective throughout the dispersion process before settling to the ground; both the temperature and the oxygen concentration (volume fraction) of the plume near the ground increased. Thus, structural optimization with an inclined exit can reduce the hazards of cryogenic exhaust plumes near the ground.

2.2 Similarity criterion

We carried out reduced-scale experiments with the vent stack of the 0.3-m cryogenic wind tunnel, to verify the design idea. The selection of the key size and exhaust parameters of the experiment was based on the similarity criteria in the wind-tunnel dispersion test. The two most important parameters are the Richardson number Ri and the Froude number Fr (Xing et al., 2014):

$$Fr=\frac{u^2}{gl},\ Ri=g\frac{\rho_{\mathrm{g}}-\rho_{\mathrm{a}}}{\rho_{\mathrm{a}}}\frac{l}{u^2}, \tag{1}$$

where l is the characteristic length, u is the velocity, ρ_{g} and ρ_{a} are the densities of the exhaust and the atmospheric air, respectively, and g is the gravitational acceleration. When using the same gas at the same temperature, one need only consider the similarity transformation of the velocity u according to the ratio between the scaled characteristic length l_{s} and the full-size characteristic length l.

To keep the Ri and the Fr of the reduced-scale test consistent with the full-size test, the relationship between velocity u_{s} in the reduced-scale test and velocity u in the full-size test should follow the relation:

$$\frac{u_{\mathrm{s}}}{u}=\left(\frac{l_{\mathrm{s}}}{l}\right)^{1/2}. \tag{2}$$

The size of the vertical exhaust pipe in the reduced-scale experiment was proportional to that of

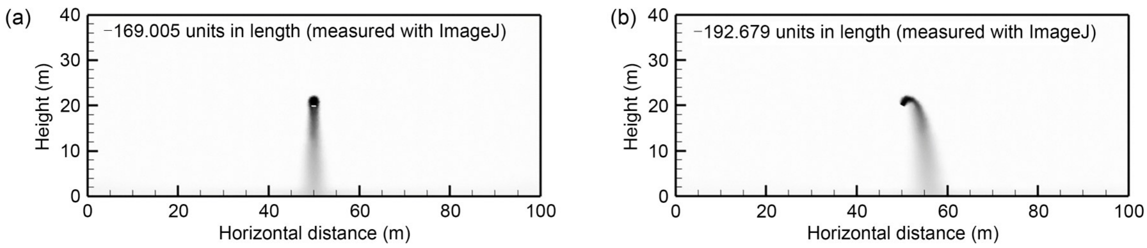

Fig. 2 Plume profiles with a conventional exit (a) and inclined exit (b)

the vent stack of the 0.3-m cryogenic wind tunnel. The height of the vent stack was 13 m, and the diameter of the exit was 0.75 m. The scaled ratio was 1/20, making the height of the exhaust pipe 65 cm, and the diameter of the exhaust exit 3.75 cm. Based on Eq. (2), the exhaust velocity of the exhaust pipe was $0.05^{1/2}$ times that of the vent stack.

In our previous study (Li et al., 2018), we verified the numerical model with experimental data from the US NTF. Based on the similarity criteria adopted in this study, we simulated the full-size scale model and the reduced-scale model of the 0.3-m cryogenic wind tunnel vent stack to verify the rationality of the reduced-scale experiment. As displayed in Table 1, for the full-size model, the reference case had an environmental wind speed of 1 m/s, exhaust flowrate of 4.12 m/s (@110 K), environmental wind temperature of 296 K, and relative humidity of 50%. Following the similarity criteria, for the reduced-scale model the parameters became: an environmental wind speed of 0.22 m/s, exhaust flowrate of 0.92 m/s (@110 K), environmental wind temperature of 296 K, and relative humidity of 50%.

Fig. 3 shows a comparison of the simulated results for cryogenic nitrogen gas dispersion in the full-size and reduced-scaled models. The ratio of the axis dimensions is 1∶20, corresponding to the reduced scale. In the full-size case, the minimum temperature and minimum oxygen concentration (C_{O_2}) of the cryogenic plume near the ground are 291.75 K and 19.95%, respectively, while the settlement location is approximately 9 m from the bottom center of the vent stack. In the reduced-scale case, the corresponding parameters are 288.78 K, 19.88%, and 0.38 m. Table 2 presents the deviations between the results of the two simulation models. Based on the parameters of the full-size model, the deviation of the distance between the minimum temperature point near the ground and the bottom center of the vent stack was −15.6% (the minus sign indicates that the reduced-scale model underestimated the distance compared to the full-size model). The deviations of temperature and the oxygen concentration were −1.02% and −0.35%, respectively. From this analysis, we deduced that the similarity criteria adopted in the study were reasonable.

2.3 Experimental system and procedure

Fig. 4 shows the configuration of the experimental system with the inclined exit. The cooling part provided cryogenic nitrogen gas with the required

Table 1 Modelling parameters for validation of the rationality of the scaled experiment

Model	Wind speed (m/s)	Wind temperature (K)	Exhaust flowrate (m/s)	Exhaust temperature (K)	Relative humidity (%)	Exit height (m)	Exit diameter (m)
Full-size	1.00	296	4.12	110	50	13.00	0.7500
Reduced-scale	0.22	296	0.92	110	50	0.65	0.0375

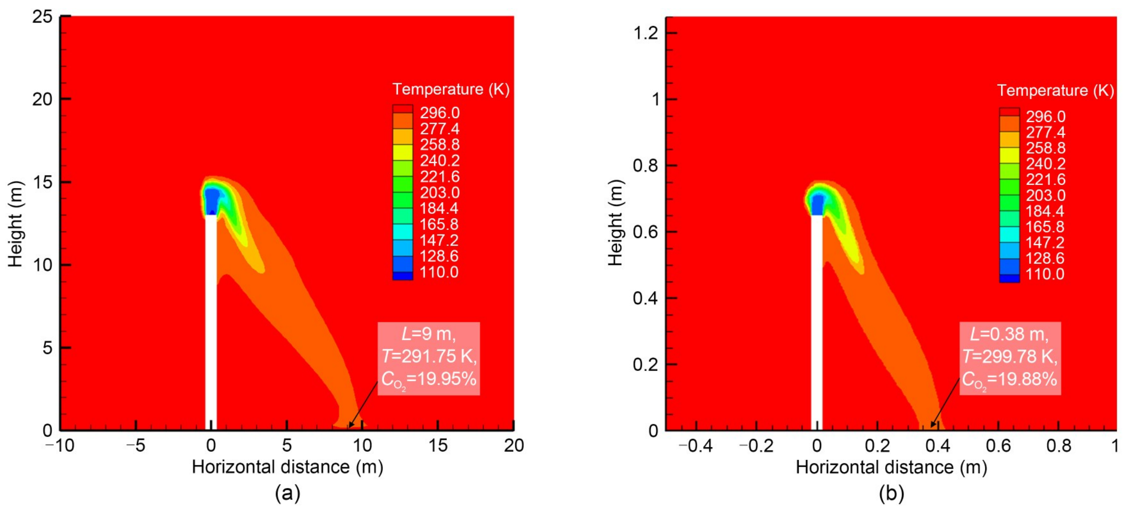

Fig. 3 Comparison of the simulation results for cryogenic nitrogen gas dispersion in the full-size (a) and reduced-scale (b) models

Table 2 Deviations between the simulated results with the full-size and reduced-scale models

Model	Minimum temperature near the ground (K)	Minimum oxygen concentration near the ground (%)	Distance downwind of the settlement location (m)
Full-size model	291.75	19.95	9.00
Reduced-scale model	288.78	19.88	0.38
Deviation (%)	−1.02	−0.35	−15.6

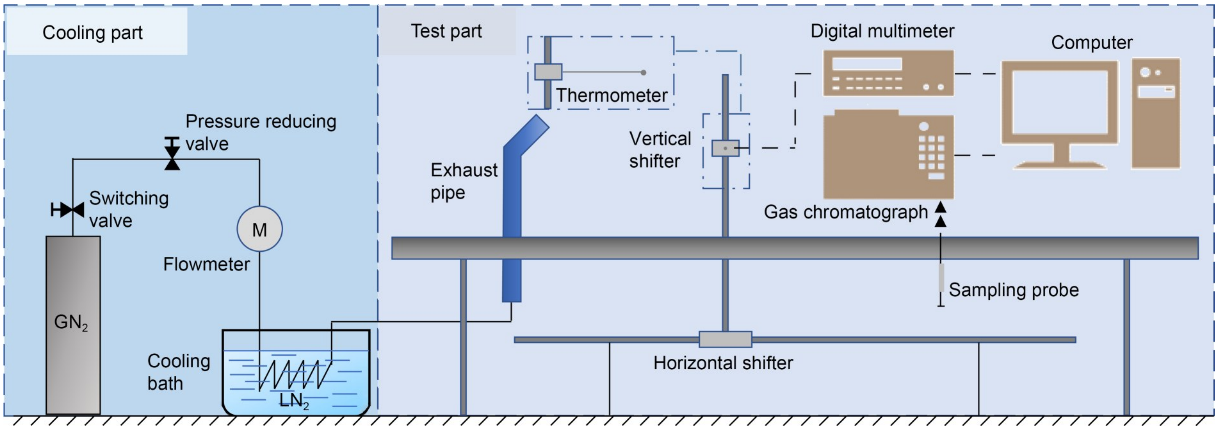

Fig. 4 Experimental system for research on the behavior of the cryogenic exhaust plume with an inclined exit

temperature and flowrate; then the cryogenic nitrogen gas was discharged from the exhaust pipe and the dispersion results were measured. The horizontal dimension of the experimental table was 1 m×2 m. To reduce interference from atmospheric airflow, the 3 m×6 m area centered on the experimental table was isolated by a 2-m high screen during the experiment.

In the cooling part, the nitrogen cylinders provided nitrogen gas and the pressure-reducing valve controlled the flowrate. By adjusting the pressure-reducing valve, the pressure after the valve could be modified to obtain the target flowrate, which was maintained after adjustment. The gas flowmeter was a Siargo-MF5612 with a measurement range of 0–300 L/min and error of ±1.5%FS. Before delivery to the test part, the nitrogen gas was cooled by a coil heat exchanger which was submerged in the liquid-nitrogen cooling bath during the experiment. The nitrogen flowrate was controlled and measured at room temperature, which significantly reduced the complexity of the experiments.

In the test part, the cryogenic nitrogen gas was discharged from the exhaust pipe, and the plume sank to a horizontal table. All pipes except the exhaust pipe were wrapped with thermal insulation material to reduce heat leakage during transportation of the gas. This also significantly increased the outer diameter of the exhaust pipe and affected the environmental flow field; thus adequate precooling of the exhaust pipe was required in every test. The water vapor in the air frosted continuously on the outer wall of the pipe, and the exhaust temperature at the exit slowly dropped to a stable value.

The exhaust pipe used in the experiment consisted of a fixed section and an adjustable section, as shown in Fig. 5. The two parts were connected by a union joint, and the adjustable section could be replaced to change the initial direction of the cryogenic nitrogen gas flow. The whole exhaust pipe had a consistent diameter and the height of the center of exit for different pipes was the same as well, as shown in Fig. 5.

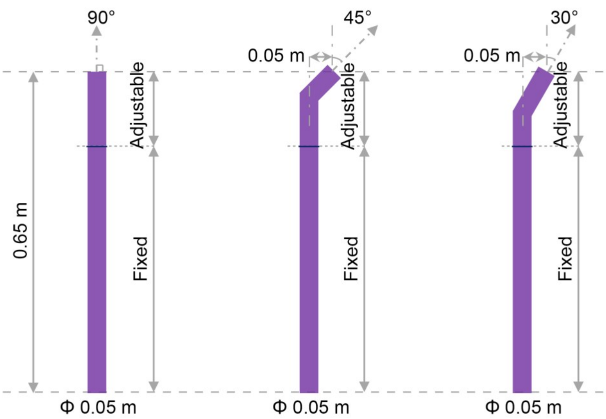

Fig. 5 Exhaust pipe exits with different angles of inclination

The temperature of the exhaust plume was measured with a PT100 platinum resistance thermometer. To measure the plume temperature at different positions, we used a 2-DOF (degree of freedom) displacement device, consisting of two stepper-motor-driven screw slide rails, to change the position of the thermometer. The slide rail of the horizontal shifter was parallel to the horizontal direction of the inclined exhaust, and the slide rail of the vertical shifter was placed upright. The vertical slide rail was fixed on the horizontal shifter. Perpendicular to the horizontal slide rail and parallel to the horizontal tabletop, a slender support rod with a diameter of 2.5 mm was arranged on the side of the vertical shifter close to the exhaust pipe. The thermometer was set at the end of the support rod furthest from the vertical shifter, positioning it just in the vertical plane where the centerline of the plume trajectory was located. A distance of 2 cm was kept between the thermometer body and the end of the support rod to avoid temperature measurement error caused by heat conduction through the support bar. The pins of the thermometer and the rest of the connection were wrapped with insulating tape. During the experiment, by controlling the stepper motors of the horizontal and vertical shifters, we adjusted the position of the thermometer to measure the plume temperature at different positions. The thermometer was mainly used to measure plume temperature at the exhaust pipe exit and near the tabletop.

The oxygen concentration of the exhaust plume in specific locations was obtained with a gas chromatograph, and gas samples at different points near the tabletop were collected with sampling probes. As shown in Fig. 4, the sampling probe was passed through the through-hole in the table board from bottom to top to avoid interfering with the flow field of the plume during sampling. Starting from the bottom center of the exhaust pipe, through-holes with a diameter of 1 mm were punched through the table board at 5-cm intervals, in the horizontal direction of the inclined exhaust. The injection port of the sampling probe was kept 1 mm above the tabletop during sampling. The sampling probe had an air-tight valve between the needle and the syringe which prevented the gas sample from being polluted by outside air. Each sampling lasted for about 10 s and the capacity of the probe syringes was 50 μL. The sampling probes were numbered, with each probe corresponding to a specific sampling site (through-hole).

The measurement process was carried out after the initial temperature and flowrate of the exhaust had stabilized. Therefore, the precooling of the system pipeline achieved by discharging cryogenic nitrogen gas at a constant rate was indispensable. A specific cryogenic exhaust flowrate was obtained by adjusting and maintaining the opening of the pressure-reducing valve. With the cryogenic nitrogen gas flowing through, the temperature of the exhaust pipe dropped slowly. The water vapor in contact with the outer surface of the exhaust pipe frosted continuously to form an ice layer and ultimately stabilize heat leakage. We considered the precooling process to be completed when the initial temperature of the exhaust at the exit remained constant ($\Delta T \leqslant 1$ K within 1 min).

The only temperature-regulating device was the coil heat exchanger in the liquid nitrogen cooling bath, and the initial temperature of the exhaust after precooling was negatively correlated with exhaust flowrate.

3 Modeling method

Compared with gas dispersion experiments carried out under ideal conditions in an environmental wind tunnel, the experiments in this study lacked an adequate gas source and a high-precision exhaust temperature control system. The non-real-time non-online gas concentration analysis method also introduces errors. Therefore, the purpose of our experiment was mainly to verify the theoretical model. Further analysis and comparison of the results were carried out based on the numerical simulations.

In our previous work, the mathematical model developed by Zhang et al. (2015) for analyzing plume dispersion from the cryogenic wind tunnel was validated (Li et al., 2018). The 3D two-phase flows, including the discharge and dispersion of the cryogenic nitrogen exhaust from the exhaust pipe, were modeled based on the Mixture model, the Realizable κ-ε model (Mcbride et al., 2001), and the Lee model. The pressure-based transient calculations for complex species transport in multiphase flows with mass transfer between the phases were solved numerically using ANSYS FLUENT (ANSYS, 2011). The thermodynamic properties of all the pure components were acquired from the databank software REFPROP, issued by National Institute of Standards and Technology (NIST, 2007).

Fig. 6 shows the corresponding computational domain for the computational fluid dynamics (CFD) simulation. The dimensions of the model were 2 m, 1 m, and 2 m in the x, y, and z directions, respectively. The bottom surface of the computational domain was the experimental tabletop and the position of the exhaust pipe was consistent with the experiment. We set the center of the bottom of the exhaust pipe as the origin of the coordinates, and the exhaust pipe with an inclined exit was symmetrical based on the y=0 m plane, which was also the plane of symmetry of the whole computational domain. Thus, the exhaust plume dispersed horizontally in the direction of the positive x-axis. The boundary in the negative x-axis direction was 0.5 m from the origin.

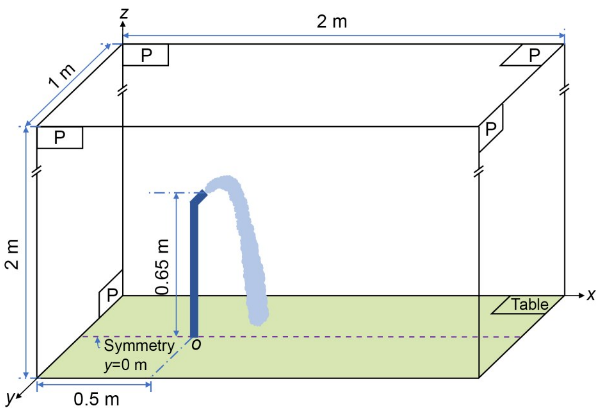

Fig. 6 Computational domain for the CFD simulation

The boundary types of the computational domain are presented in Table 3. In previous studies on gas dispersion under environmental wind conditions, the inlet air velocity (velocity-inlet) was applied to the left surface, the constant pressure (pressure-outlet) was applied to the right surface, and for the front and rear surfaces, as well as the top surface, which presumably were far enough from the plume, the boundary types were specified as the symmetry condition (Chan et al., 1984). In the present study, the exhaust plume dispersed under windless conditions. Therefore, different from previous studies, the boundary types of all the environmental boundaries were applied to the constant pressure to simulate the open environment, as listed in Table 3. Conventionally, the boundary type of the table is specified as the heat-insulated wall (Ermak et al., 1989; Luketa-Hanlin et al., 2007).

Table 3 Boundary types of the computational domain

Boundary location	Boundary type
N_2-exhaust (outlet of the exhaust pipe)	Velocity-inlet
Left surface (x=−0.5 m)	Pressure-outlet
Right surface (x=1.5 m)	Pressure-outlet
Front surface (y=0.5 m)	Pressure-outlet
Rear surface (y=−0.5 m)	Pressure-outlet
Top surface (z=2 m)	Pressure-outlet
Bottom surface (table, z=0 m)	Wall

4 Results and analyses

We carried out experiments with different nitrogen flowrates for each of the three exhaust incline angles of 0° (vertical), 30°, and 45°. During the experiment, the environmental temperature in the laboratory was 285 K and the relative humidity was 57%. In each experiment, the pre-cooling process of the exhaust pipe, until the temperature was stabilized, took about 20 min. The entire experimental cycle lasted about 40–60 min. Three nitrogen gas cylinders (for each: 40 L@15 MPa) connected by a busbar were used to provide the nitrogen gas for the experiment. As the pressure in the nitrogen gas cylinders decreased, the maximum flowrate that could be obtained decreased. Meanwhile, the flowrate had to be kept constant. Considering the limit of the available gas source, the upper limit of the nitrogen flowrate was set to 70 L/min (at room temperature). Larger flowrates such as 80 L/min or 90 L/min could not be maintained for a single experiment due to the gas-source limit.

The exhaust parameters are shown in Table 4. The volume flowrates of nitrogen gas at room temperature (V_r) were 30 L/min, 50 L/min, and 70 L/min, corresponding to the converted cryogenic nitrogen exhaust velocities (U_e) of 0.285 m/s (exhaust temperature (T_e)=180 K), 0.421 m/s (T_e=155 K), and 0.514 m/s (T_e=135 K). The exhaust parameters for the most extreme operating condition of the real 0.3-m cryogenic wind tunnel (full-size model), were an exhaust temperature of 110 K and exhaust mass flowrate of 5.6 kg/s. For the reduced-scale model, these parameters were converted to V_r=155 L/min (U_e=0.855 m/s), and T_e= 110 K. As a supplement to our main simulations, we simulated and analyzed this most extreme case.

Experimental and simulated results near the tabletop along the horizontal direction of exhaust dispersion, with inclined exits at different angles, are

Table 4 Exhaust parameters for experiment and simulation

Volume flowrate of GN_2 at room temperature, V_r (L/min)	Exhaust velocity, U_e (m/s)	Exhaust temperature, T_e (K)
30	0.285	180
50	0.421	155
70	0.514	135
155 (simulation)	0.885 (simulation)	110 (simulation)

given in Fig. 7. V_r was constant within a single group: V_r=30 L/min (T_e=180 K) in Group A, V_r=50 L/min (T_e=155 K) in Group B, and V_r=70 L/min (T_e=135 K) in Group C. In each group, the upper part shows the temperature results at z=1 mm and the lower part shows the oxygen concentration results at z=1 mm.

It should be noted that the temperature results measured in this experiment were not values but ranges, because the dispersion process of the plume was accompanied by strong turbulence which can be described based on the Kelvin-Helmholtz instability theory (Kuhlman and Prahl, 1975; Saïd et al., 2005), and which causes the state of the plume to fluctuate within a range. Therefore, the temperature measurement for each position lasted more than 2 min to obtain the corresponding temperature-fluctuation range. The oxygen concentration measurement method with probe sampling and gas chromatograph analysis, was not adequate for real-time monitoring of gas oxygen concentration. Thus, the speed of the sampling probe was slowed down to obtain an average oxygen concentration value.

In the cases with an inclined exit of 30° or 45°, the horizontal component of the velocity of the exhaust provided the horizontal movement trend for the plume. Therefore, the settlement position of the cryogenic plume from the inclined exit (shown as the lowest point of the oxygen concentration trend or temperature trend in Fig. 7) was always far away from the exhaust pipe. However, it is notable that there was an abnormal experimental temperature trend near the exhaust pipe in every case with an inclined exit. Theoretically, as shown in the simulation curve, the local temperature and distance from the settlement point should be positively correlated. Taking the experimental case shown in Fig. 8 as an example, although the settlement position was located at approximately x=0.19 m, the temperature near the tabletop at x=0.05 m was lower than the temperature at x=0.1 m. A reasonable explanation for the abnormal temperature trend near the pipe is that heat leakage from the pipe wall affected the surrounding tabletop, causing the local temperature to drop.

The comparison results in Fig. 7 show that the model was reasonably accurate. In predicting the dispersion results of the plume near the tabletop, the discrepancy of the temperature was <5.0%, and the discrepancy of the oxygen concentration was <5.5%. The analyses indicated that the numerical model can be further used to demonstrate the advantages of the new exhaust method with an inclined exit.

4.1 Discussion of simulations

In the cases with a vertical exhaust pipe, the cryogenic gas sinks against the outer wall of the pipe. Unlike the free settlement in a barrier-free open environment, the exhaust pipe wall is located in the center of the settling path of the plume, which may affect the mixing of cryogenic nitrogen gas with atmospheric air. In the simulation, the exhaust pipe wall was assumed to be adiabatic; thus its leakage was not considered. Fig. 9 presents the temperature results of the plume from the vertical pipe and the vertical exit without the wall, for the conditions V_r=70 L/min and T_e=135 K. For the vertical exit without a wall, only the exit surface of the exhaust pipe was retained, and the part below the exit was deleted and replaced by the environment. The presence of a pipe wall makes the minimum plume temperature near the pipe slightly lower, and the maximum temperature difference at z=1 mm is 1.4 K. When the distance from the exit increases, the temperature difference decreases. The temperature difference is 0.2 K at x=0.3 m, and 0.1 K at x=0.5 m. In conclusion, the influence of the pipe wall on the settlement result is not significant. The vertical pipe model with a wall could be used in further simulation and comparison.

The minimum temperature and minimum oxygen concentration of the plume near the ground are two key parameters for judging the degree of hazard the cryogenic nitrogen exhaust brings to the public environment. The influences of exhaust temperature and flowrate on cryogenic nitrogen plume dispersion were analyzed in our previous work (Li et al., 2018).

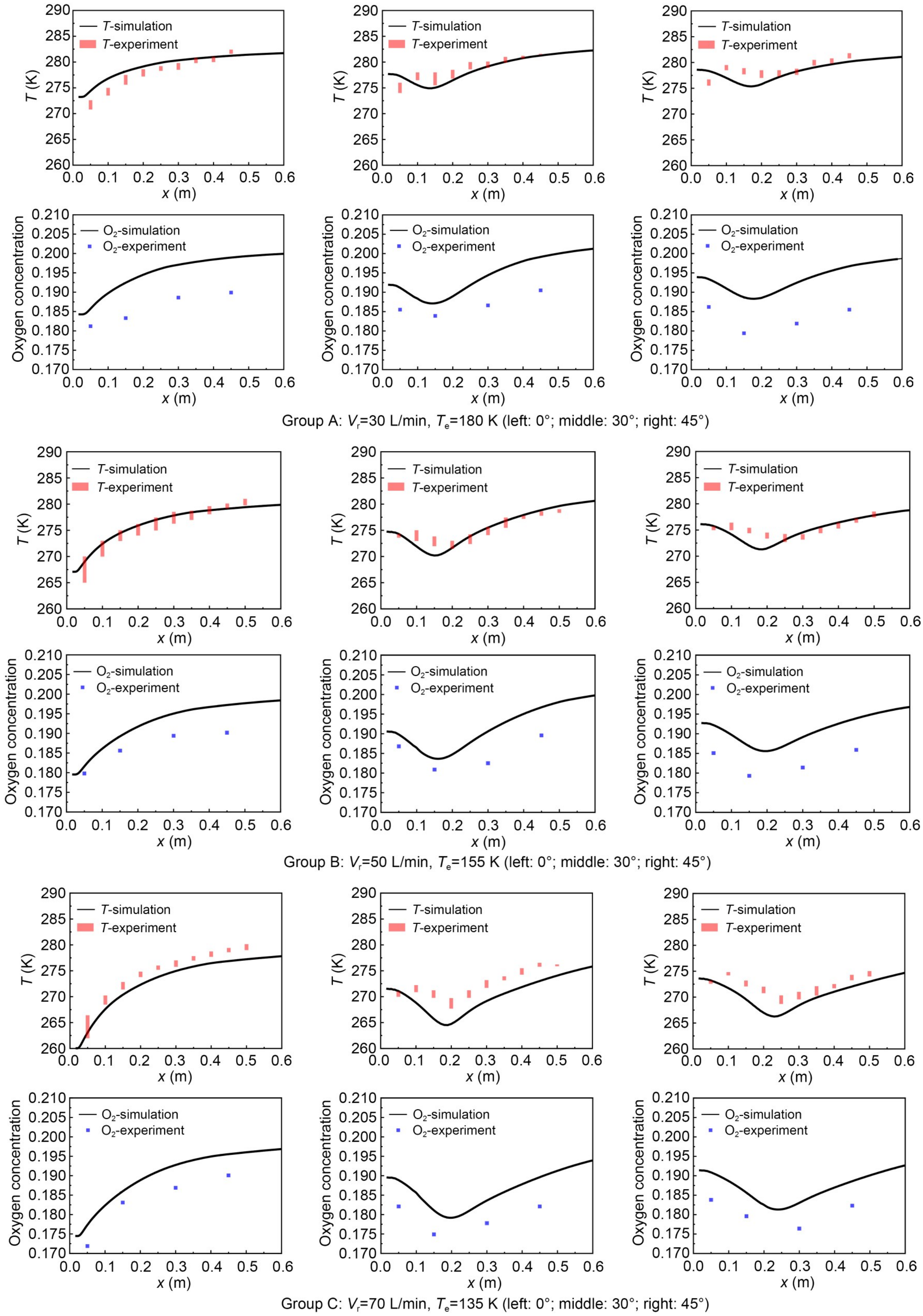

Fig. 7 Experimental and simulated results at z=1 mm with exits inclined at different angles. In each group, the upper part shows the temperature results at z=1 mm and the lower part shows the oxygen concentration results at z=1 mm

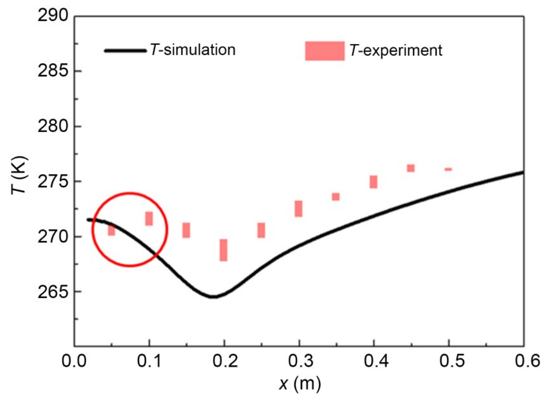

Fig. 8 Abnormal simulated temperature trend near the exhaust pipe at z=1 mm (V_r=70 L/min, T_e=135 K, 30°)

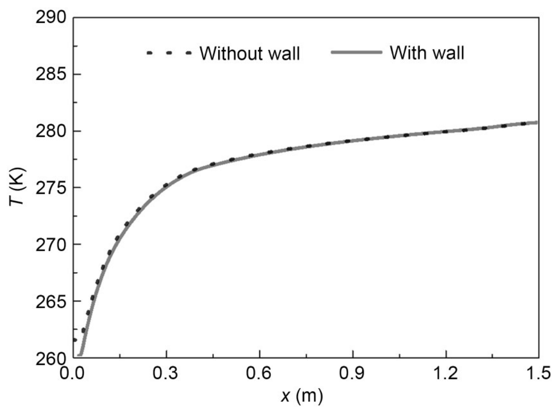

Fig. 9 Effect of the pipe wall on the temperature curve of the plume at z=1 mm (V_r=70 L/min, T_e=135 K, 0°)

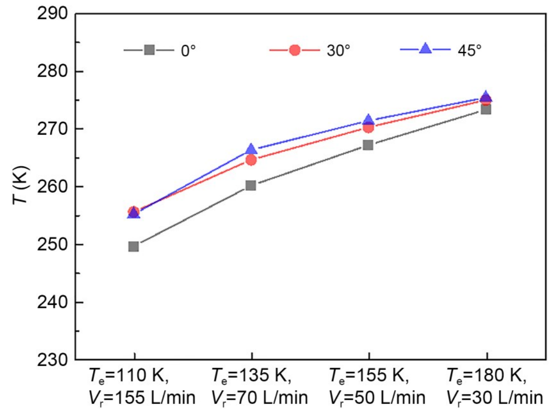

Fig. 10 Simulated minimum temperatures at z=1 mm with different angles of inclination

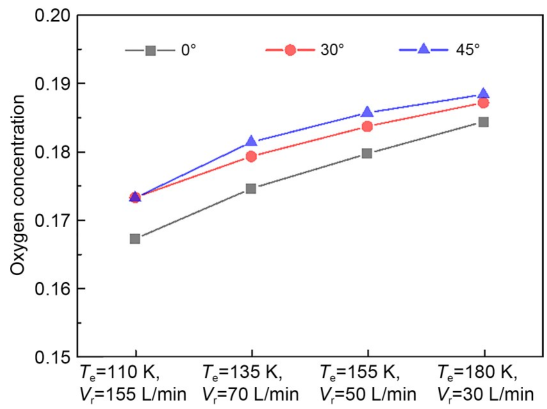

Fig. 11 Simulated minimum oxygen concentrations at z=1 mm with different angles of inclination

Meanwhile, univariate experimental study on the exhaust temperature T_e or exhaust flowrate V_r cannot be conducted based on the existing experimental system. Thus, in this study, the analysis focuses on the influence of the angle of inclination of the exit. Figs. 10 and 11 show analyses of the reduced-scale simulation results for minimum temperatures and minimum oxygen concentrations at z=1 mm, with different angles of inclination.

In terms of the simulation results, the new exhaust method with an inclined exit has an obvious effect in reducing the hazard of the cryogenic plume, and the more severe the exhaust conditions ($V_r\uparrow$, $T_e\downarrow$), the better the effect. In cases with an inclined angle of 45°, the degrees of frostbite damage and oxygen deficiency caused by the cryogenic dense gas settlement are slightly lower than in corresponding cases with an inclined angle of 30°. Under exhaust conditions of V_r=155 L/min, T_e=110 K, the difference in the minimum temperature (as well as the minimum oxygen concentration) between the cases with an inclined angle of 30° and an inclined angle of 45° is negligible. Similarly, the difference in minimum temperature under exhaust conditions of V_r=30 L/min, T_e=180 K is negligible, while the difference in the minimum oxygen concentration is also slight.

4.2 Energy-saving potential

For a certain nitrogen flowrate, the minimum temperature of the plume from the inclined exit near the ground is higher than with the traditional vertical exit, while the exhaust temperature is the same. In other words, when the nitrogen flowrate is fixed, to obtain the same minimum temperature near the ground, the exhaust temperature of a plume from the traditional vertical exit needs to be appropriately higher than a plume from an inclined exit. As mentioned earlier, natural gas burners can be used to raise the exhaust temperature to reduce potential hazards. The proposed exhaust method with an inclined exit reduces the need for burners to obtain safe plume-settlement results, allowing lower energy consumption.

For the real 0.3-m cryogenic wind tunnel (full-size model), the lower limit of the exhaust temperature T_e is 110 K and the upper limit of the exhaust mass flowrate is 5.6 kg/s. We considered freezing to be the criterion for the effect of low temperature, and thus chose 273 K as the safe lower limit for temperature. The safe lower limit was set as 18.5% for oxygen concentration. The weather conditions were ideal conditions with a wind speed of 0 m/s, an atmospheric temperature of 285 K, and a relative humidity of 57%. With the constant exhaust mass flowrate fixed at 5.6 kg/s, simulations were performed every 25 K, starting from the exhaust temperature T_e=110 K. As shown in Fig. 12, according to the safety standards mentioned above, the cryogenic nitrogen gas needs to be heated to about 230 K with the conventional vertical-exhaust method, while the proposed method (with an inclined exit of 30° or 45°) only requires a temperature of approximately 210 K. Therefore, the exhaust method with an inclined exit clearly reduces the hazard of the cryogenic plume.

The heating power Q is calculated by enthalpy difference:

$$Q=(h_{T2}-h_{T1})\,\dot{m}, \tag{3}$$

where h_{T1} and h_{T2} represent the specific enthalpies of nitrogen gas at different temperatures, and $\dot{m}$ is the mass flowrate of the cryogenic nitrogen exhaust. Using the database software REFPROP, $h_{110\,\mathrm{K}}$=112 kJ/kg, $h_{210\,\mathrm{K}}$=218 kJ/kg, and $h_{230\,\mathrm{K}}$=238 kJ/kg.

Under windless conditions, assuming that only a natural gas burner is used to heat the cryogenic nitrogen gas to reduce the plume hazard, and without considering heat leakage from the vent stack, the heating power required is 706 kW with the conventional vertical exhaust method; it is only 594 kW with an inclined exit of 30° or 45°. Thus, this energy-free structural optimization with an inclined exit can save heating-energy consumption while meeting the same emission safety standards. In the above example, 15.9% of heating-energy consumption can be saved by the proposed method. In practice, the ejectors and the fans are used prior to the burner, so 15.9% is the theoretical maximum energy-saving ratio.

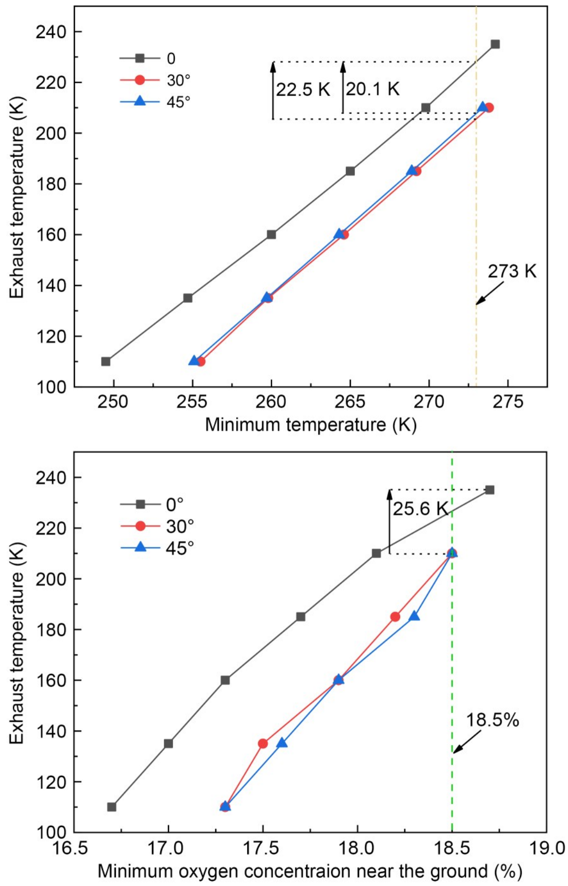

Fig. 12 Simulated plume dispersion results at z=1 mm with different inclined-angle exits with different exhaust temperatures. The upper part shows the temperature results at z=1 mm and the lower part shows the oxygen concentration results at z=1 mm

5 Conclusions

We propose a new exhaust method with an inclined exit for cryogenic wind tunnels. We conducted reduced-scale experiments based on similarity criteria, with the vent stack of the 0.3-m cryogenic wind tunnel as a reference. The experimental data, the numerical model describing the complex species transport in multiphase flows with mass transfer between the phases is verified to have reasonable accuracy to predict the dispersion result of the cryogenic plume, with the discrepancy of the temperature <5.0%, and the discrepancy of the oxygen concentration <5.5%. The comparative analysis based on the experimental and further simulation results shows that the new exhaust method with the inclined exit of 30° or 45° can effectively reduce the settlement hazard of the cryogenic plume, compared with the conventional vertical exhaust method, and the more severe the exhaust conditions ($V_r\uparrow$, $T_e\downarrow$), the better the effect.

The theoretical energy-saving potential of the new exhaust method with an inclined exit is calculated by taking the extreme exhaust case of the 0.3-m cryogenic wind tunnel as an example. Compared with a burner, this energy-free structural optimization with a 30° or 45° inclined exit can save up to 15.9% of heating energy consumption under windless conditions, while meeting the same emission safety standards. In addition, the new exhaust method with an inclined exit can raise the safe lower limit of the exhaust system.

In future studies, further consideration should be given to the influence of environmental wind speed and direction on the exhaust process of cryogenic nitrogen gas based on an inclined wind-tunnel exit. Finally, the optimal angle of inclination and horizontal angle between exit and wind should be obtained, with different weather and exhaust parameters.

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Author contributions

Jingfeng LI and Limin QIU designed the research. Jingfeng LI and Chenjie GU processed the corresponding data. Jingfeng LI wrote the first draft of the manuscript. Kai WANG helped to organize the manuscript. Jingfeng LI and Kai WANG revised and edited the final version.

Conflict of interest

Jingfeng LI, Kai WANG, Chenjie GU, and Limin QIU declare that they have no conflict of interest.

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