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A parametric sensitivity study by numerical simulations on plume dispersion of the exhaust from a cryogenic wind tunnel

Key words:
Cryogenic wind tunnel; Plume dispersion; CFD; Phase change

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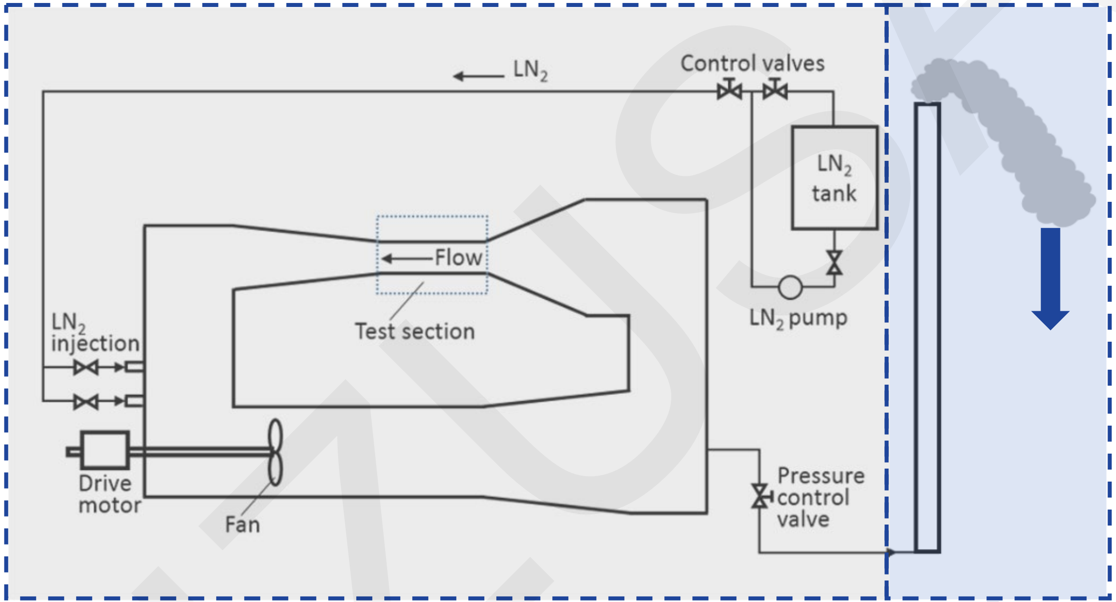
Motivation

The low temperature environment in the cryogenic wind tunnel is achieved by injecting liquid nitrogen through small nozzles positioned in the wind tunnel circuit upstream of the driven fan. Then the liquid sprayed into the tunnel is vaporized and the cold nitrogen gas is accelerated as the test gas.



In order to keep steady thermodynamic conditions for testing, it is necessary to exhaust the cold nitrogen gas from the tunnel through an exhaust stack, at the same mass flow rate as that of the liquid nitrogen which is continuously injected.

A large amount of low temperature nitrogen gas, denser than the ambient air, may sink down, posing potential hazards to the public such as frostbite damage and oxygen deficiency.

CFD model considering the phase change of water

Continuity, momentum and energy equations

$$\frac{\partial}{\partial t}(\rho_m)+\nabla\cdot(\rho_m\bar{u}_m)=0$$

$$\frac{\partial}{\partial t}(\rho_m\bar{u}_m)+\nabla\cdot(\rho_m\bar{u}_m\bar{u}_m)=-\nabla p+\nabla\cdot\left[\mu_m\left(\nabla\bar{u}_m+\nabla\bar{u}_m^t\right)\right]+\rho_m g$$
$$+\nabla\cdot\left[\sum_{k=1}^{2}\left(\alpha_k\rho_k\bar{u}_{dr,k}\bar{u}_{dr,k}\right)\right]$$

$$\frac{\partial}{\partial t}\sum_{k=1}^{2}(\alpha_k\rho_k E_k)+\nabla\cdot\sum_{k=1}^{2}\left[\alpha_k\bar{u}_k(\alpha_k E_k+p)\right]=\nabla\cdot\left(k_{eff}\nabla T\right)+S_E$$

Volume fraction equation

$$\frac{\partial}{\partial t}(\alpha_g\rho_g)+\nabla\cdot\left(\alpha_g\rho_g\bar{u}_m\right)=\dot{m}_{lg}-\dot{m}_{gl}$$

Species mass conservation equation

$$\frac{\partial}{\partial t}(\rho_g\alpha_g Y_{g,i})+\nabla\cdot\left(\rho_g\alpha_g\bar{u}Y_{g,i}\right)=-\nabla\cdot\alpha_g\bar{J}_{g,i}+\sum_{i=1}^{2}\left(\dot{m}_{lg,i}-\dot{m}_{gl,i}\right)$$

Species mass conservation equation

$$\text{Evaporation }(T_l>T_{sat}):\dot{m}_{lg}=C_{ev}\cdot\alpha_l\cdot\left[\alpha_l\rho_l\left(\frac{T_l-T_{sat}}{T_{sat}}\right)\right]$$

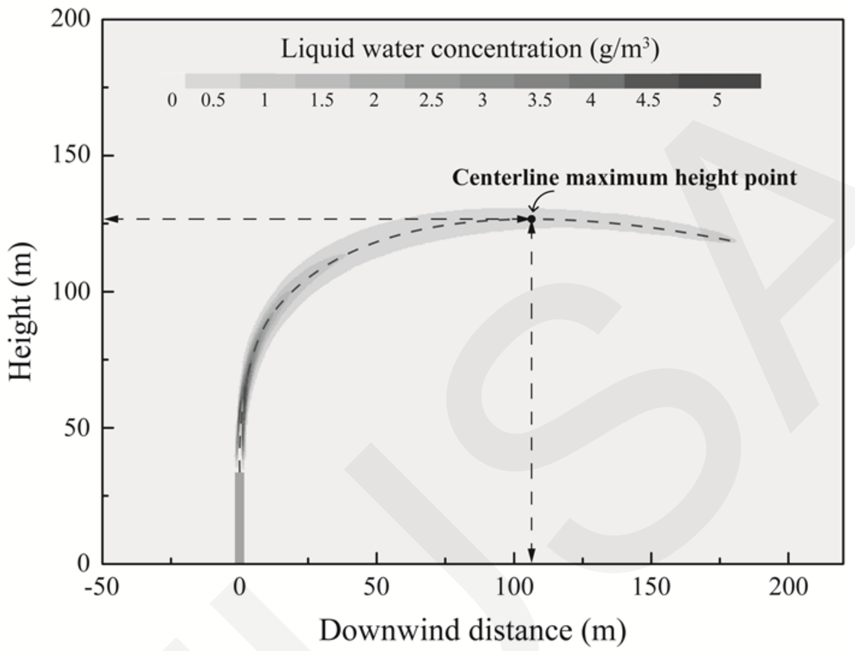
$$\text{Condensation }(T_g<T_{sat}):\dot{m}_{gl}=C_{con}\cdot\chi\cdot\left[\alpha_g\rho_l\left(\frac{T_v-T_{sat}}{T_{sat}}\right)\right]$$

Turbulence model（Realizable *κ*-*ε*）

$$\frac{\partial}{\partial t}(\rho_m\kappa)+\frac{\partial}{\partial x_j}\left(\rho_m\bar{u}_{m,j}\kappa\right)=\frac{\partial}{\partial x_j}\left[\left(\mu_m+\frac{\mu_m^t}{\sigma_k}\right)\frac{\partial\kappa}{\partial x_j}\right]+G_\kappa+G_b-\rho_m\varepsilon$$

$$\frac{\partial}{\partial t}(\rho_m\varepsilon)+\frac{\partial}{\partial x_j}\left(\rho_m\bar{u}_{m,j}\varepsilon\right)=\frac{\partial}{\partial x_j}\left[\left(\mu_m+\frac{\mu_m^t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right]$$
$$+\rho_m C_1 S\varepsilon-\rho_m C_2\frac{\varepsilon^2}{\kappa+\sqrt{\nu\varepsilon}}+C_{1\varepsilon}\frac{\varepsilon}{\kappa}C_{3\varepsilon}G_b$$

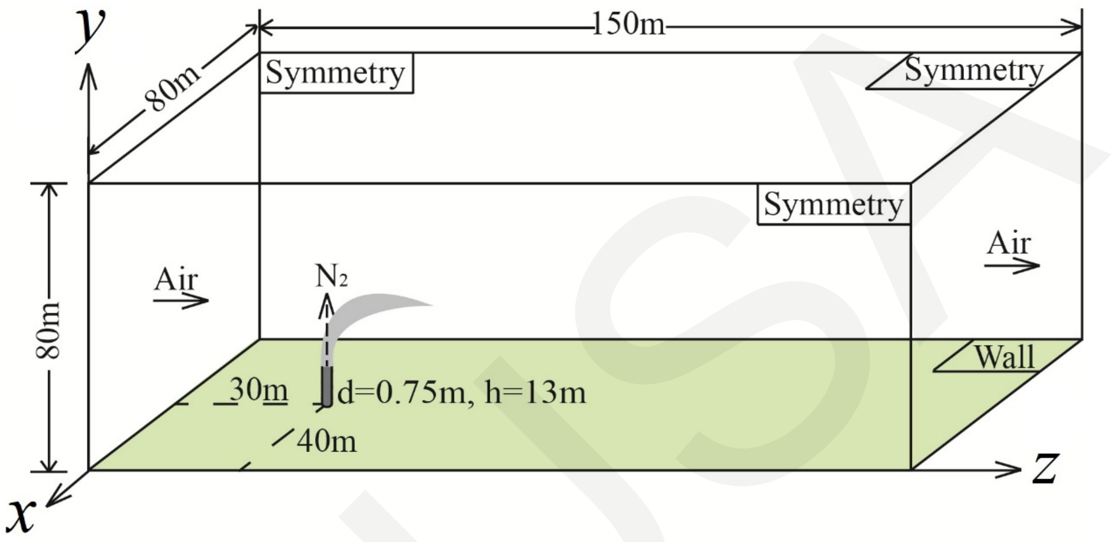
Model validation



Parameter	Experiment	NASA’s model	Present model
Centerline maximum height (m)	10.9^a 119^b	116.7^a (10.2%) 135^b (13.4%)	107.3^a (1.3%) 127^b (6.7%)
Distance downwind of centerline at maximum height (m)	59.7^a 97.3^b	120.5^a (101.8%) 148.8^b (52.9%)	77.7^a (30.2%) 106.3^b (9.3%)

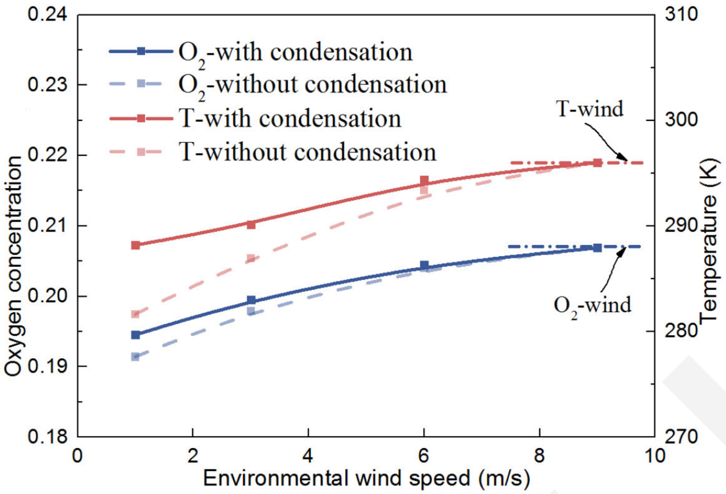
Superscript a: 207.7 kg/s nitrogen flow rate; b: 270.7 kg/s nitrogen flow rate. The deviations are inside the brackets.

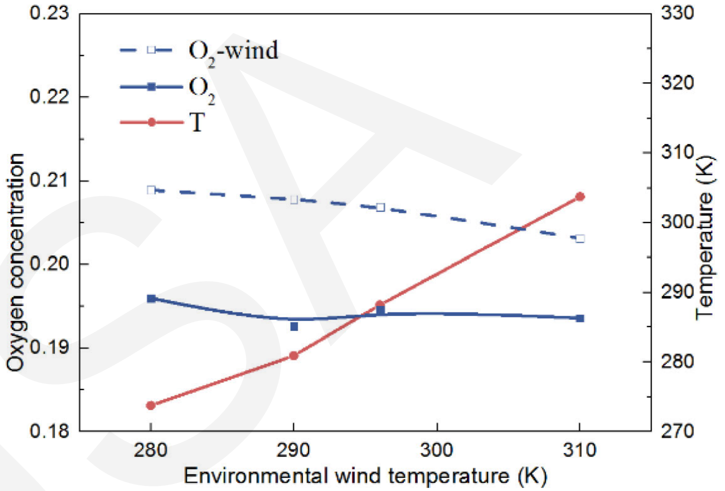
Problem description and boundary condition

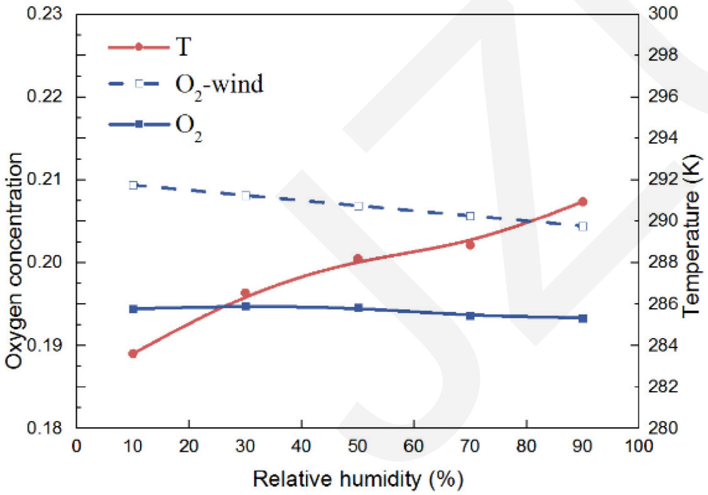


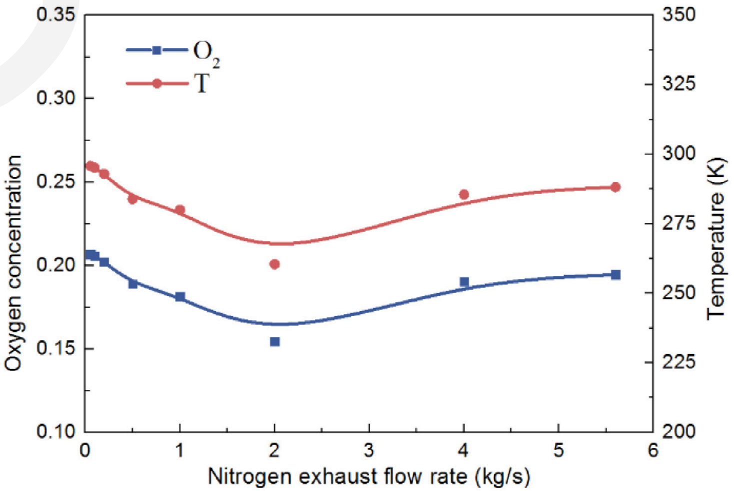
Boundary name	Boundary type
Air-inlet (left)	Velocity-inlet
N_2-inlet (top of the stack)	Velocity-inlet
Air-outlet (right)	Pressure-outlet
Top	Symmetry
Front/rear	Symmetry
Ground	Wall

The influences of key parameters

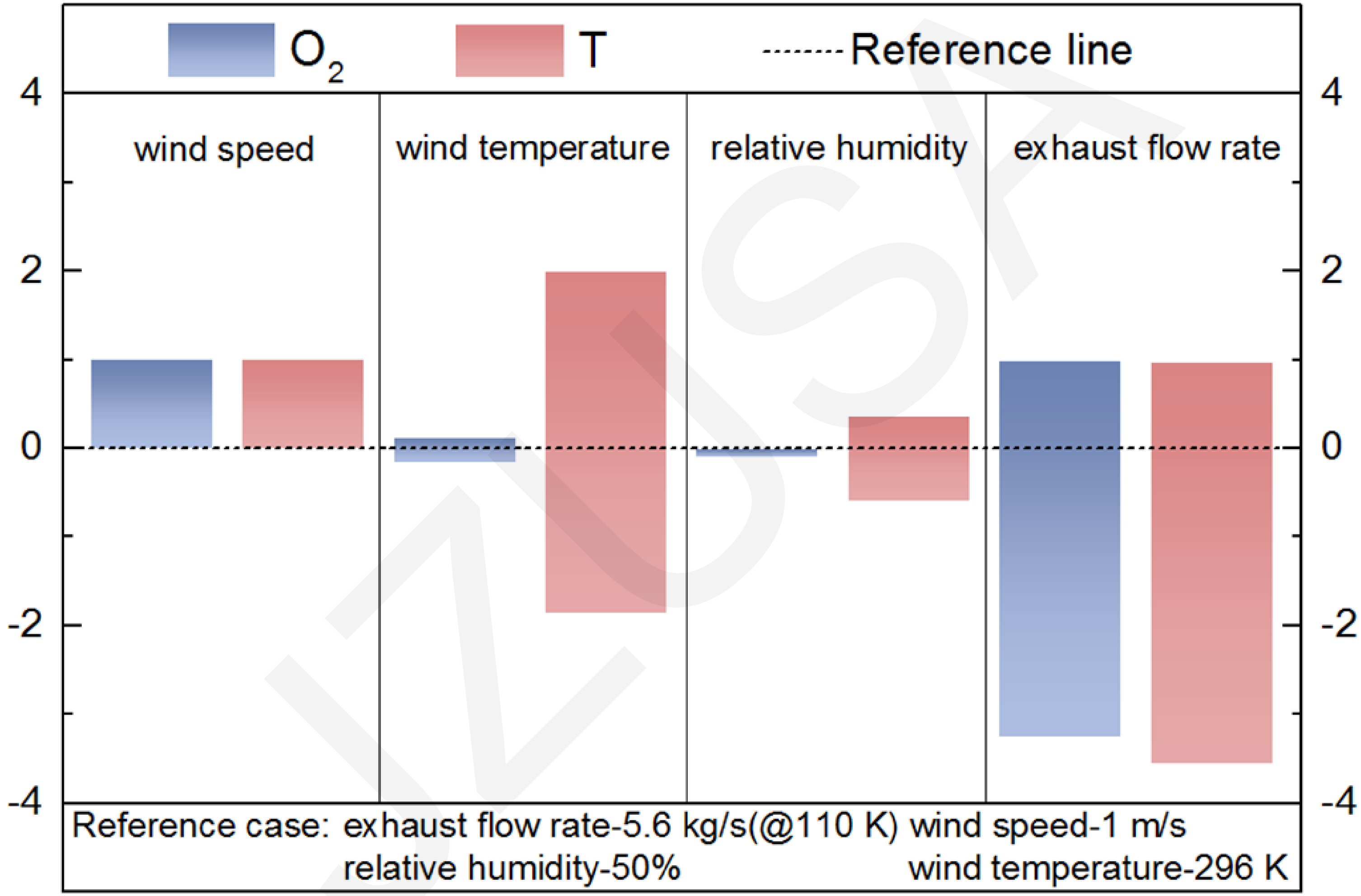








Effect sensitivities of different influence factors



Reference case: exhaust flow rate-5.6 kg/s(@110 K) wind speed-1 m/s
relative humidity-50% wind temperature-296 K

Conclusions

- The CFD calculations with the present model considering the phase change of water are more consistent with the experimental data than those of NASA's two-stage analytical model. It can provide acceptable accurate quantitative risk assessments of the cryogenic plume flow behavior to avoid the potential hazards.

- Higher environmental wind speeds are conducive to the plume dissipation in respect of oxygen and temperature.

- Higher environmental wind temperature and relative humidity have a positive impact on plume temperature near the ground, while the oxygen concentration near the ground slightly fluctuates with higher environmental wind temperature and slightly decreases with higher relative humidity.

- At a flow rate less than 2 kg/s, the gas accumulation effect brought by rising flow rate leads to a negative effect on plume dissipation. When the flow rate is higher than 2 kg/s, increasing flow rates have a positive effect on plume dissipation, since a larger initial kinetic energy results in a longer distance for descent.