Annual Report 2023 JMBC – Research Highlight

This highlight refers to the PhD Thesis by Rui Yang (2023, cum laude)

Turbulent flows with phase changes

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Phase-change transitions are well-established phenomena in the scientific community, representing the transformation of matter between its various states: solid, liquid, gaseous, and plasma. Melting, the process of changing matter from a solid to a liquid state, and solidification, the reverse process, are familiar examples. Consider, for instance, making ice cubes from water (solidification) or converting ice cubes back to water (melting). Similarly, matter can transition from its liquid state to the gaseous state, known as evaporation, and the reverse process is termed condensation. Daily examples of evaporation include the boiling of water, leading to water vapour, and the aerosol droplets generated from coughing and sneezing, while condensation occurs when water vapour forms water droplets on a mirror after a hot bath. The study focuses on two classes of phase-change transitions: melting and freezing (Part I) and evaporation and condensation (Part II). These transitions have diverse applications, ranging from industrial to environmental scenarios. Throughout the study, we emphasize the interaction between phase-change and turbulent flows, and how this interaction influences the overall phase-change process.

Part I. Melting and Freezing (Ice melting)

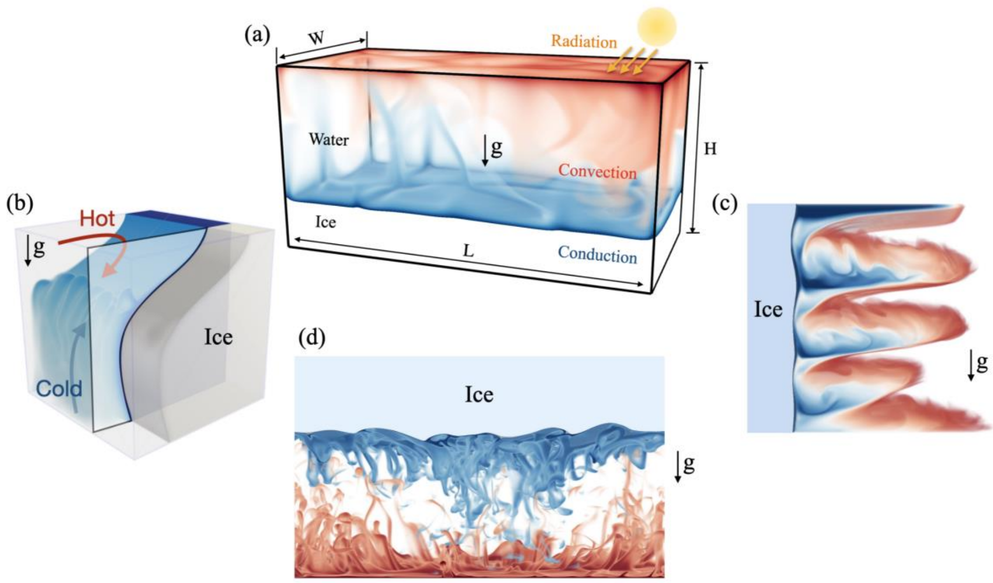

Figure 1: Summary of the melting geometries we studied in our numerical melting studies: (a) Melt pond dynamics under solar radiation (Yang et al. 2023b); (b) Sidewall melting in fresh water (Yang et al., 2022a); (c) Sidewall melting in saline water (Yang et al. 2023a); (d) Basal melting under turbulent thermal convection (Yang et al., 2023c).

The quantitative understanding of glacial ice melting into the ocean is one of the most outstanding challenges in environmental fluid dynamics. The lack of knowledge is on a fundamental level, due to the highly complex multi-scale, multi-physics nature of the problem. The process involves intricate multi-way coupling effects including thermal convection, salinity, ocean current, and radiation, etc. As ice melts into the surrounding salty water, a decrease in local salt concentration leads to reduced water density, inducing upward buoyant forces and consequently upward flow. This flow dynamically interacts with the ice, resulting in a feedback loop of further melting (Stefan problem).

Our investigation employs direct numerical simulations with the phase field method. To capture the intricacies of melting dynamics within turbulent flows, we implement a multiple-resolution strategy for salinity and phase field simulations 0. The versatility of our method is demonstrated through successful applications to diverse melting scenarios, including the formation of melt ponds 0, melting in Rayleigh-Bénard (RB) convection (Yang et al., 2023c), vertical convection with fresh water (Yang et al., 2022a), and vertical convection with salty water 0. We showcase results obtained across these various geometries, see Figure 1. This work contributes to advancing our understanding of the complex dynamics involved in glacial ice melting within oceanic environments.

More specifically, we examined basal melting through heating from below (RB convection) and observed the emergence of topographical structures evolving from initially smooth surfaces due to the underlying convective flow. We further quantified the roughness scaling with the strength of the thermal driving and determined the horizontal length scale using theoretical upper and lower bounds. Our proposed theory successfully predicts the trends in numerical results (Yang et al., 2023c). Moving forward, we delved into the temperature oscillation effect on heat transfer and melt rate in RB convection, which relates to diurnal and seasonal cycles in natural systems. Our findings indicated a significant enhancement in heat transfer depending on the frequency due to boundary layer perturbations caused by modulation. We further proposed frequency-dependent Stokes thermal boundary. Based on its interplay with the thermal and velocity boundary layer in RB convection, we derived theoretical scalings for the onset and optimal frequency for heat transfer enhancement (Yang et al., 2020). Continuing our exploration, we investigated surface melting by solar radiative heating from above and analyzed the evolution of melt ponds. This study revealed the bistability of melt pond formation, which means under the same parameters, the melt pond can either form or disappear, depending on the initial condition. This bistability was explained through the balance of interface heat flux (Yang et al., 2023b). Additionally, we focused on ice sidewall melting in freshwater (Yang et al., 2022a) and saline water 0. In freshwater, we observed an abrupt increase in the melt rate with rising ambient temperature, attributed to changes in flow structure due to the density anomaly effect in freshwater. In saline water, we studied the evolution of the layered structure of melting ice, which is quantitatively consistent to the previous experiments. We further observed a non-monotonic dependence of the melt rate on salinity, understanding it as a result of the competition among salinity-driven buoyancy, temperature-driven buoyancy, and salinity-induced stratification.

Part II. Evaporation and Condensation (Respiratory droplet spreading)

This part primarily focuses on the evaporation and condensation processes concerning respiratory droplets, particularly in scenarios like coughing flows with microdroplets and indoor ventilation, which significantly contributes to the spread of infectious diseases. Understanding the interaction between droplets and ambient turbulent flows is essential in this context. Droplets or particles suspended in the air can act as carriers for respiratory viruses, making it scientifically vital to study their motion and evaporation processes to comprehend virus transmission. The dispersion of droplets/particles in the air is a complex multiphase and multiscale fluid dynamics problem, influenced by various factors, including environmental flow, human movements, convective heat generated by the human body, and the jets produced during coughing and sneezing.

We employ direct numerical simulations to investigate a turbulent respiratory event and study the evolution of microdroplets in turbulent flow using the point particle approach. Numerical simulations offer real-time tracking of droplets or particles and provide detailed physical parameters, offering a more effective way to understand their dispersion compared to experimental measurements. The effects of ambient temperature and RH are investigated (Chong et al, 2020; Ng et al., 2021), which can be applied for large-scale parameterizations. Additionally, we utilize DNS, fully coupled with temperature, CO_2, and water vapour concentration fields, to examine indoor mechanical displacement ventilation across a wide range of ventilation rates and its impact on CO_2 removal and air quality, as well as its interaction with the flow pattern (Yang et al., 2022b).

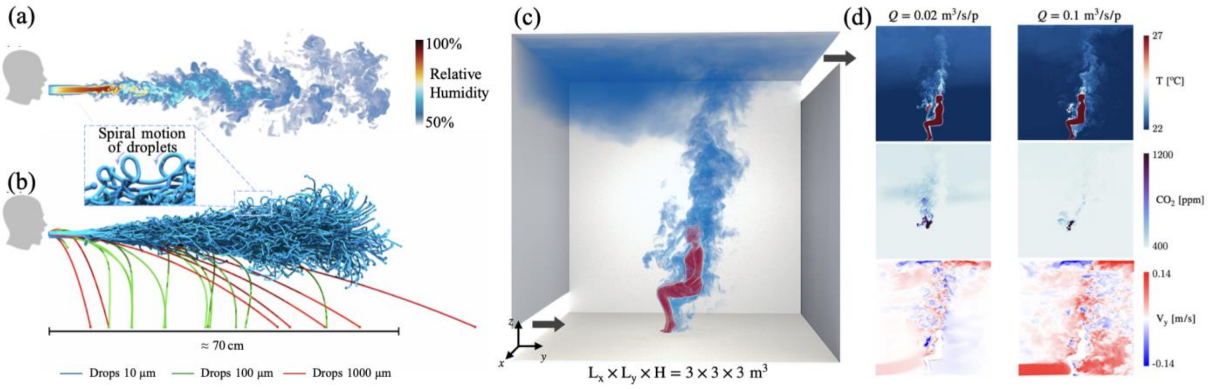

Figure 2: (a) Contour snapshot and (b) droplet trajectories of the droplet-laden cough simulation. (c) Illustration of the simulation setup with the body plume, breathing flow, and arrows indicates the inlet and outlet flows and (d) Temperature, CO_2 field and horizontal velocity of ventilated flows for different flow rates.

Firstly, we delved into the dynamics of microdroplet evaporation in a coughing flow, including quantifying the lifetime of the droplets in the turbulent and humid coughing puff (Chong et al., 2020) and analyzing the impact of ambient temperature and humidity on the droplet lifetime (Ng et al, 2021). We made a significant discovery that small droplets (with an initial diameter of 10 µm) are entrained by turbulent eddies in the expelled humid puff, see Figure 2(a-b), resulting in an extension of their lifetime by a factor of more than 30 compared to scenarios without the puff. We further conducted a detailed investigation of various ambient temperature and humidity conditions, and proposed a model for the axial relative humidity (RH) based on the assumption of a quasistationary jet, which accurately predicted super-saturated RH conditions in our simulations. Shifting our focus to a larger scale, we explored the effect of indoor displacement ventilation rate Q on the clean zone height h with a human present, sitting, and breathing inside the room, see Figure 2(c-d). We found that for weak ventilation, the interface height follows a scaling relation $h \sim Q^{3/5}$. However, for excessively strong ventilation, the interface height h becomes insensitive to Q. In summary, our study provided valuable insights into the evaporation and condensation processes in different pandemic-related scenarios, contributing to a better understanding of the dynamics of microdroplets and the impact of ventilation rates on clean zone heights (Yang et al. 2022b).

Conclusion

The study has demonstrated that multiphase flow, with multiple components and phase transitions, is extremely rich, with a huge phase space and many, often counterintuitive phenomena. These flows are of utmost relevance in nature & technology, and our analysis only scratches on this field, or speak in the language of our research field, is only the tip of an iceberg. Many new phenomena remain be discovered and explained, and we expect a boost of activity on this subject in the upcoming decade.

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