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Special Issue on Recent Hot Topics in Rarefied Gas Dynamics

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ABSTRACT
Rarefied gas flows are present in a wide range of scientific and technological problems, such as hypersonic vehicles flying at very high altitudes, propulsion systems of spacecraft navigating in space, and vacuum devices operating on the ground. To continue engagement in the rarefied gas dynamics (RGD) community and bring together researchers, the 'Pre-RGD32 Online Workshop on Recent Hot Topics in Rarefied Gas Dynamics' was held during July 7-10th, 2021. This special issue presents a selection of papers from the workshop, highlighting works of innovative CFD research and developments of a fundamental or applied nature, and their applications to the field of rarefied gas dynamics.

Rarefied gas flows—gas flows in a low-density state—are present in a wide range of scientific and technological problems. Such flows can be found in hypersonic vehicles flying at very high altitudes, propulsion systems of spacecraft navigating in space, and vacuum devices operating on the ground.

In the field of rarefied hypersonics, Zahm (1934), a leading aviation pioneer of the United States, boldly proposed in his paper 'Superaerodynamics' that Newton's theory of air resistance (Newton 1729; von Kármán 1942), which assumed that fluids were noninteracting equidistant uniform particles, was suitable for calculating the lift and drag forces of an object in rarefied hypersonic flows. In 1934, a general explanation of the resistance of fluids was already possible through Navier-Stokes equations derived a century earlier and Prandtl's boundary layer theory published in 1904. Moreover, the so-called thin-airfoil theory was developed as early as 1922, and the basic understanding of airfoil aerodynamics (lift coefficient $2\pi\alpha$) was well established. Therefore Zahm's proposal to turn the clock two centuries back was considered reckless.

Later, Tsien (1946) of Caltech in the US developed key concepts that are fundamental to current rarefied aerodynamics, such as long-range rocket vehicle aerodynamics, viscous stresses and boundary conditions in slip flow, Burnett extended constitutive equation models, and free molecular flow characteristics at high Mach numbers.

On October 4, 1957, the Soviet Union successfully launched Sputnik 1 to the elliptical low-Earth orbit. The success of the satellite sparked the Sputnik shock around the world, especially in the United States, and the space race between major powers began in earnest. In the field of rarefied gas dynamics (RGD), the 1st International Symposium on Rarefied Gas Dynamics was held in Nice, France in 1958, the year after the launch of Sputnik. Since then, it has been held every two years.

The 32nd International Symposium on Rarefied Gas Dynamics (RGD32; www.rgd32.org)—a biannual event in RGD originally scheduled in July 2020, Seoul, Republic of Korea—was postponed to the summer of 2022 due to the COVID-19 pandemic. To continue engagement in the RGD community and bring together researchers, especially graduate students, RGD32-LOC along with the International Advisory Committee (IAC) decided to hold the 'Pre-RGD32 Online Workshop on Recent Hot Topics in Rarefied Gas Dynamics' during July 7–10th, 2021.

Applications for presentations came from 26 different countries and other areas worldwide. The final programme included 3 invited plenary lectures and 105 contributed presentations over 3 days. The

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workshop covered theoretical, computational, and experimental studies on topics such as rarefied gases, micro- and nano-scale flows and heat transfer, and hypersonics as well as emerging topics such as plumes and surface interaction in space, Lagrangian methods for the BGK model, and data-driven & machine-learning-based mesoscale modelling.

This special issue presents a selection of papers from the workshop, highlighting works of innovative CFD research and developments of a fundamental or applied nature, and their applications to the field of rarefied gas dynamics.

Chourushi et al. (2021) present an explicit mixed-type modal discontinuous Galerkin method based on the second-order Boltzmann-Curtiss constitutive model and the Maxwell slip and Smoluchowski jump conditions. They conducted a comprehensive analysis for different configurations of re-entry vehicles under various degrees of rarefaction.

Schouler, Prévereaud, and Mieussens (2021) perform a simulation of the Intermediate eXperimental Vehicle (IXV) with a CFD solver in rarefied regimes and compare it with the DSMC results. They also investigated the atmospheric model effect on flight data reconstruction and applied it to the early phase of the IXV reentry.

Appar and Kumar (2021) present a coupled flow-thermal solver to study the atmospheric reentry phenomenon in the rarefied regime. A direct simulation Monte Carlo flow solver was coupled with a material thermal response solver at the fluid-solid interface by exchanging and updating the interface properties at certain anchor points along the reentry trajectory.

Giroux and McDonald (2021) present an approximation to closing fluxes of the twenty-one-moment maximum-entropy model that offers a hyperbolic treatment of viscous flows exhibiting heat transfer. They applied the proposed approximation to the shock structure problem in rarefied gas dynamics and demonstrated that the results are in better agreement with the Boltzmann equation than the Navier-Stokes equations.

Zhu, Zhong, and Xu (2021) analyze the variations of kinetic schemes and obtain the corresponding governing equations in the continuum flow regime. In the design of the multiscale method with the unified preserving property, the general requirement for recovering the Navier-Stokes solution from an operator-splitting kinetic method is presented and validated numerically.

Tiwari, Klar, and Russo (2021) present a liquid droplet moving inside a rarefied gas, where the interface deformation in space and time has been captured by coupling the BGK model for the gas phase and the incompressible Navier-Stokes solution for the liquid phase. The BGK equation is solved by a semi-Lagrangian scheme with a mesh-free reconstruction procedure, while the incompressible Navier-Stokes solution is obtained by a mesh-free particle method.

Garcia Perez and Suzuki (2021) introduce a new plasma-surface interaction simulation programme called Solar Corona-Spacecraft Interaction (SCSI). SCSI is designed with an object-oriented approach and is composed of a set of numerical methods to run almost independently in different regions. The programme is tested by simulating the interaction of a satellite with the solar wind. Results demonstrate the capability of the programme to capture the main physical phenomena present in plasma-surface systems.

In summary, these seven papers together provided a view into current developments in computational physics modelling and CFD solver in the field of rarefied gas dynamics. We thank the authors who have worked hard to prepare full versions of their papers.

The papers were refereed, each evaluated by two independent reviewers. We would like to take this opportunity to thank all anonymous reviewers for their time and commitment.

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