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PROPOSITION DE SUJET DE THESE

Intitulé : Boundary layer observation in convection using advanced optical diagnostics

Référence : **MFE-DAAA-2026-20**
(à rappeler dans toute correspondance)

Début de la thèse : October 2026	**Date limite de candidature :**

Mots clés

Convection, Scalar dissipation, Turbulent heat transfer, Thermographic PIV, Dynamic Light Scattering

Profil et compétences recherchées

MSc in Fluid Mechanics. Experience in data processing and a curiosity for optical measurements.

Présentation du projet doctoral, contexte et objectif

Natural turbulent convection is one of the main drivers of geophysical and astrophysical flows (another being rotation). Stars, like the sun, have a convective zone that efficiently evacuates the heat generated by the thermonuclear reactions in their core. Convection is also at play in planets and many satellites, ensuring efficient heat transport and turbulent mixing. On Earth's atmosphere, it applies at many scales from local updrafts to the entire tropospheric layer. It also drives the mixing between oceanic layers and the motion of ocean currents. Hence, it is a fundamental mechanism for meteorological and climate forecasting. Concerning Earth's interior, convection is involved in plate tectonics and dynamo action. Natural convection is also the most secure cooling procedure in the industry because it does not involve pumping mechanisms or heat exchangers.

Because of its significance, thermal convection is a problem that has long been debated in physics. A most common approach consists in establishing power laws between relevant dimensionless parameters like the Nusselt number (Nu), which is the dimensionless heat flux, and the Rayleigh number (Ra), proportional to the imposed temperature gradient. There is the expectation that, in the turbulent regime, one can extend the law of heat transport established in the laboratory to other situations where dimensionless parameters take asymptotically large values. Indeed, it is believed that once we reach a highly turbulent regime where molecular diffusivities do not play any role in transport efficiency (0th law of turbulence) an ultimate regime occurs imposing the law $Nu \propto \sqrt{Ra}$. Nevertheless, an extension of laboratory results to natural flows is far from obvious because of the various geometries and boundary conditions encountered.

The canonical setup to study heat transport by convection in the laboratory is the so-called Rayleigh-Bénard (RB) setup. In such a device, the convective fluid is sandwiched between solid plates at fixed temperatures. This imposes boundary layers (BL), of depth λ, limiting the heat transport. In that case, another less efficient law of transport is predicted: $Nu \propto Ra^{1/3}$. Bypassing the limiting effect of this layer by increasing the forcing further appears to be difficult, although the BL should destabilize. Surprisingly, there is no experimental agreement about the law of heat transport above a given forcing ($Ra>10^{11}$). None of them provides clear and indisputable evidence of a transition to the ultimate regime without tricks. Such tricks try to break or bypass the BL. This can be done for instance with a radiative heating in which the light-absorbing length is larger than the BL. Artificial rough plates can also break the BL when λ and roughness lengthscale are of the same order [1]. In any case, the knowledge of the boundary layer state (linear vs turbulent) is necessary to predict heat transport and explain the discrepancies between experiments. Direct Numerical Simulations (DNS) also fail to capture transition to ultimate regime.

In this thesis, advanced optical diagnostics will be applied to probe the boundary layer state and heat transport in a Rayleigh Bénard experiment with multi scale roughness on the bottom plate.

The method which will be implemented will be:

Diffusing wave spectroscopy (DWS)

It is widely accepted from theoretical considerations that the state of the BL and the level of dissipation in it, might influence the law of heat transport and the transition between different regimes. Dissipation rate in the BL is difficult to measure with usual techniques because it implies an estimate of all the components of the velocity in all directions with high accuracy to compute the norm of the strain rate tensor (the dissipation being proportional to its square). We have developed at CEA an innovative technique for mapping directly the norm of the strain rate tensor at the boundary of turbulent flow [2]: the Diffusing Wave Spectroscopy (DWS). This technique uses a coherent laser to illuminate a turbid (milky-like) fluids seeded with submicron scatterers. By the study of the dynamics of the interference speckle pattern of the backscattered light, we are able to get maps of the dissipation resolved in time at the boundary of turbulent flows. It should be perfectly suitable to measure the mean dissipation rate at the top of a convective cell and the level of its fluctuations. We will therefore be able to test directly the theoretical prediction correlating the rate of dissipation in the BL with the law of heat transport

Thermographic particle Image Velocimetry (thermographic PTV)

The previous measurements probe the heat flux at the boundary, but to get a full understanding of heat transport one must understand how the BL fluctuations affect the heat transport as it goes deeper into the bulk of the convective cell where turbulent advective transport dominates. To answer this question, we plan to combine the knowledge of Particle Image Velocimetry (PIV) or tracking (PTV) acquired at CEA with the ONERA ability to perform sensitive optical thermometry techniques with solid photo-luminescent tracer particles [3]. The goal is to simultaneously measure the vertical velocity w in a horizontal plane with stereo PIV and obtain the temperature, θ*, and temperature gradient,* $\partial\theta\partial z$*, in the same plane, using the solid particles for both PIV and dual-plane thermometry. The product* $w\theta$ *will give the advective part of the heat flux in a horizontal plane, resolved in space and time.* $\partial\theta\partial z$ *gives access to the conductive counterpart of the heat flux. Combined temperature and velocity measurements have been performed in RB convection using liquid crystals and Laser Induced Fluorescence encapsulated particles. However, a systematic study of the horizontal in-plane fluctuations of the advective part of the heat flux from the BL to the bulk is, to our knowledge, still lacking, although there is a high scientific value in capturing the interplay of heat flux in the BL and in the bulk especially in the case where turbulent BL are forced by rough surfaces. To reach the required level of resolution, we will use the luminescent particle technique developed and used at ONERA over thermochromic. Owing to the method of temperature reading which is based on measuring the luminescence lifetime approach, measurements are, unlike for thermochromic liquid crystals, independent of observation angle and therefore temperature induced refraction effects. Moreover, the spectral shift between illumination and detection avoids the effects of surface reflections, and the luminescent particles have a much* ***faster response*** *(<100 µs). Due to recent development in particle materials,* ***a higher level of precision*** *(0.3 K) than fluorescent tracers could can be achieved. These particles will be implemented in the CEA large facility to be combine with the best velocimetry methods mastered by CEA. It will allow simultaneous measurement of the temperature and vertical velocity. In addition, using a scanning light sheet approach, we propose to determine the temperature in closely spaced planes, to access the conductive term too.*

References:

[1] V. Bouillaut, S. Lepot, S. Aumaître, B. Gallet, Journal of Fluid Mechanics. 2019;861:R5.
[2] E. Francisco, J. Lambret, S. Aumaître, submitted to Phys. Rev. Fluids
[3] C. Abram, B. Fond & F. Beyrau, Progress in Energy and Combustion Science ***64*** *(2018)*

Collaborations envisagées

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