Available online at www.sciencedirect.com
SCIENCE DIRECT®
Physica B 329–333 (2003) 429–430
PHYSICA B
www.elsevier.com/locate/physb

Thermal turbulence in cryogenic helium gas

J.J. Niemela[a,]*, K.R. Sreenivasan[b]

[a] *Department of Physics, Cryogenic Helium Turbulence Laboratory, 1274 University of Oregon, Eugene, OR 97403, USA*
[b] *Institute for Physical Sciences and Technology, University of Maryland, College Park, MD 20742, USA*

Abstract

Several recent experiments have utilized cryogenic helium gas in order to generate high levels of thermal turbulence within a layer of gas heated from below. As the principal control parameter for the fluid turbulence depends strongly on the layer height, this has typically been made as large as feasible, while the lateral dimensions have been kept of the same dimension or smaller for practical reasons. While we continue to learn many important things from small aspect ratio experiments, implications and limitations of this lateral confinement are discussed, given our current understanding of the nature of large scale recirculating flows in developed turbulent convection.

Keywords: Turbulent convection; Heat transfer; Large scale circulation

1. Introduction

Turbulent thermal convection is ubiquitous in nature and in engineering, and plays a prominent role in the energy transport within stars, atmospheric and oceanic circulations, the generation of the earth's magnetic field, and innumerable engineering processes in which heat transport is an important factor. It is fundamentally a difficult problem, with a large number of spatial and temporal degrees of freedom and strong interactions between scales.

In an idealization of the problem, the so-called Rayleigh–Bénard convection, the fluid is confined between two horizontal surfaces a distance H apart and heated from below, resulting in a vertical temperature difference ΔT. Time scales for heat and momentum diffusion and buoyancy are $\tau_\vartheta = H^2/\kappa$, $\tau_v = H^2/\nu$, and $\tau_B = (H/\alpha g \Delta T)^{1/2}$, where ν, κ, α, and g are respectively the kinematic viscosity, thermal diffusivity, isobaric coefficient of thermal expansion, and gravitational acceleration. Two dynamical similarity parameters, the Rayleigh (Ra) and Prandtl (Pr) numbers specify the dynamical state of the flow and can be obtained from ratios of time scales: $Ra = \tau_\vartheta \tau_v/\tau_B^2 = (\alpha \Delta T g H^3)/(\nu\kappa)$ and $Pr = \tau_\vartheta/\tau_v = \nu/\kappa$.

2. Observations

Details of the apparatus are described in Ref. [1]; here, we cite only a few salient features. The working fluid is helium gas at a nominal temperature near 5 K. Adjustment of the pressure (density) results in roughly 12 decades variation of Ra. The top and bottom plates were made of annealed copper, and spaced up to 100 cm apart vertically. Cylindrical lateral walls of diameter $D = 50$ cm, were made of thin stainless steel. The aspect ratio $\Gamma = D/H$, was $\frac{1}{2}$ or 1 depending on whether sidewalls having the full height, or half of it, were used.

A principal observable is the Nusselt number, Nu, which is the effective thermal conductivity of the fluid, normalized by its molecular value. A large scale circulation (LSC) exists for Ra up to at least 10^{13}, and its velocity is inferred from the time-correlation of small resistance thermometers. Details of these latter measurements are presented in Refs. [1–3]. Because of the LSC, Γ becomes an important additional parameter.

The LSC has a number of interesting properties. As discussed in Refs. [2,3] it exhibits sudden and irregular

---

*Corresponding author.
E-mail address: joe@vortex.uoregon.edu (J.J. Niemela).

0921-4526/03/$ - see front matter © 2003 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0921-4526(02)02327-X

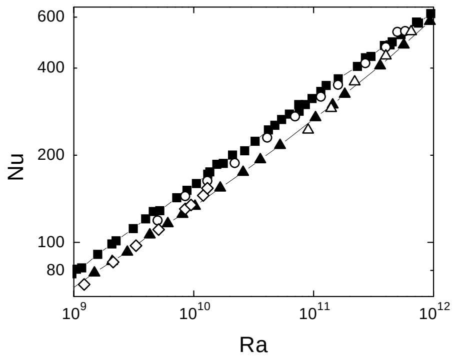

Fig. 1. *Nu* vs. *Ra*. Filled squares, Ref. [1]; filled triangles, Ref. [7]; open symbols, Ref. [8]. There appear to be two main branches of *Nu* consistent with the existence of two distinct modes of the LSC.

reversals of its direction. The probability distribution function of reversal intervals has a self-similar distribution of scales up to some large time scale [3], beyond which it falls off exponentially (indicating a Poisson-like process). These and other observations of the LSC are shown in Ref. [3] to be consistent with the concept of self-organized criticality [4].

If we suspend consideration of the LSC for the moment and focus on the thermal boundary layers on the top and bottom heated surfaces, a simple model [5] dictates that they grow diffusively with a thickness $\delta \propto \sqrt{\kappa t}$, become depleted through the emission of "plumes" when their size increases past some limit for marginal stability, and grow again in a periodic process. If the interior flow is sufficiently mixed (high *Ra*) the two boundary layers act independently, the physical heat flux is independent of the layer height, and we expect the "classical" $Nu \sim Ra^{1/3}$ scaling to hold. The LSC, however, connects the top and bottom surfaces, and can modify the boundary layers in a number of ways, including rendering them turbulent, and thus can have a substantial impact on the realized heat transfer.

The confinement of small aspect ratio containers can complicate the situation, as shown by the recent numerical experiments of Verzicco and Camussi [6] and consistent with recent measurements. Modeling convection in a $\Gamma = \frac{1}{2}$ container with rigid, adiabatic lateral boundaries, and $Pr = 0.7$, Verzicco and Camussi observe that the LSC can change from a single roll to two equal vertically stacked rolls for $Ra \sim 10^9$. Fig. 1 illustrates experimental observations which are consistent with the existence of such different hydrodynamic modes. Here, we plot Nusselt numbers from helium experiments, obtained in both $\Gamma = 1$ and $\frac{1}{2}$ containers. The data from Refs. [1,7] were obtained in the same apparatus except for a change in aspect ratio from $\frac{1}{2}$ to 1. The other data are from Roche [8] for aspect ratio $\frac{1}{2}$ only, but taken under nominally identical operating conditions. The two apparent groupings of the data are uncorrelated with *Pr* or Γ, or changes in active experimental features or protocol. Roche et al. [9] have suggested that differences within their data may indeed result from distinct hydrodynamic modes, and our present data [7] and simulations [6] are consistent with this conjecture. Since the stacked arrangement does not occur in simulations [10] for $\Gamma = 1$, we might furthermore conjecture that the data of Ref. [1] and some of the data of Ref. [8] correspond more to the stacked LSC case, leading to an enhanced heat transfer, while those of Ref. [7] and the other data of Ref. [8] more likely correspond to a single roll. While there remains much to learn from small aspect ratio experiments, as a consequence of these observations we conclude that it would be of significant, further interest to extend measurements to containers with reasonably larger Γ, say $\Gamma \sim 4$, given the apparent importance of the LSC in turbulent convection.

Acknowledgements

The authors wish to acknowledge ongoing collaborations with R.J. Donnelly and L. Skrbek, and stimulating discussions with G. Ahlers, B. Castaing, P. Roche, and R. Verzicco. The research was supported by the NSF grant DMR-95-29609.

References

[1] J.J. Niemela, L. Skrbek, K.R. Sreenivasan, R.J. Donnelly, Nature 404 (2000) 837.
[2] J.J. Niemela, L. Skrbek, K.R. Sreenivasan, R.J. Donnelly, J. Fluid Mech. 449 (2001) 169.
[3] K.R. Sreenivasan, A. Bershadskii, J.J. Niemela, Phys. Rev. E 65 (2002) 563-06.
[4] P. Bak, How Nature Works, Copernicus, New York, 1996.
[5] L.N. Howard, in: H. Görtler (Ed.), Proceedings of the 11th International Congress on Applied Mechanics, Springer, Berlin, 1966, pp. 1109–1115.
[6] R. Verzicco, R. Camussi, preprint, 2002.
[7] J.J. Niemela, K.R. Sreenivasan, J. Fluid Mech. (2002), in press.
[8] P.E. Roche, Ph.D. Thesis, Centre de Recherche sur les Trés Basses Températures Laboratoire CNRS associé á l'Université Joseph Fourier, 2001.
[9] P.E. Roche, B. Castaing, B. Chabaud, B. Hebral, preprint, 2002.
[10] R. Verzicco, R. Camussi, J. Fluid Mech. 383 (1999) 55.