INTRODUCTION

The specificity of the Solid-Fluid Transfer group relies in its know-how in Heat transfer and Energetics. Another characteristic is that almost any member of the group is or was an experimentalist, or, if not, closely works with experimentalists. In the broad field of Heat transfer and Energetics, which is constantly revisited by new experimental techniques (e.g. optical velocimetry), new materials, or new challenges (e.g. micro- and nano-scales), the Solid-Fluid Transfer group explores four domains: (1) two-phase flows, (2) oscillating flows, (3) heat transfer from solid to superfluid helium, and (4) applications of convective transfers. Scientific results obtained in each theme are described further on; they also correspond to specific skills that we have developed. Globally speaking, our experimental skills are:

- Particle Image Velocimetry, Laser Doppler Velocimetry, Piezoelectric pressure sensors, for studying acoustic streaming of various intensity in thermoacoustic / acoustic resonators;
- Hot wires in an oscillating fluid, for cases where optical velocimetry techniques cannot be used;
- Thermal probes (temperature, fluxes) in cryogenics conditions, for studying the Kapitza resistance at cryogenic temperatures;

Considering numerical simulations, some of us develop numerical codes with advanced numerical techniques; most of us mainly use numerical codes and contribute partially to their development. Globally speaking, the numerical skills developed in the group are:

- HPC and massively parallel Divergence-free two-phase flows with front-tracking for studying Faraday waves and related issues (massively parallel computing);
- Flows combining a Low-Mach-number region with an incompressible one, including front-tracking, for two-phase flows at microscale (accurate numerical scheme);
- Flows with microfluidic suspensions (asymptotic expansions, perturbation methods);
- Incompressible flows in open domains for natural convection in buildings (adapted boundary conditions);
- Second law analyses of processes, especially of solar-powered ones and those for refrigeration.

Our common purpose is to correctly simulate and finely understand the basic phenomena involved in complex or innovative transfer problems. Beyond fundamental knowledge, we are interested in improving the efficiency of transfer processes, e.g. via intensification of heat-transfer, separation, energetic efficiency, or reduction of irreversibilities. We thus address issues related to thermal- or energy-engineering, and we try to build bridges between theoretical investigations and applications. We are involved in various applications such as heat-transfers at nano-scales, solar air-conditioning, design of superconducting cavities of particle accelerators, or emergency-cooling of nuclear reactors.

It must be also said that the skills listed above have often been developed with the precious help of other people in the Mechanical-Engineering Department, namely F. Lusseyran (AERO group) for PIV and LDV techniques, J. Chergui (CIGITA) for parallelization of numerical codes with front-tracking or with thermal problems, V. Daru and P. Le Quéré (AERO group) for numerical simulation of two-phase flows, Y. Fraigneau (CIGITA) for implementing pressure-driven boundary conditions on open domains.

In short, the Solid-Fluid Transfer group currently consists of two CNRS researchers, one professor, six assistant professors, one research engineer (only half-time for the group), and five PhD students. We collaborate with various French laboratories, namely FAST, IPNO, PMMH, CEA/IRFU, CEA/LITEN, EM2C, Pprime, LAUM, PIMENT, IEF, LGEp, LadHyX, IRSTEA, and foreign institutions like Hongik Univ. (South Korea), Univ. Chile, ETH (Zürich, Switzerland), Univ. Houari Boumediene (Algeria), Univ. Marrakech (Morocco), École Polytechnique Tunisie, IPPT in Acad. Sci. and Univ. Warsaw (Warsaw, Poland), Zhukovsky Inst. and Inst. Phys. Chem. and Electrochem. Russian Acad. Sci. (Moscow, Russia), Tech. Inst. Phys. Chem. Beijing, Inst. Refrig. and Cryog. Zhejiang Univ., Hangzhou (China), and MIT (USA).
RESEARCH ACTIVITIES

TOPIC 1: TWO-PHASE FLOWS, DYNAMICS AND TRANSFERS

M.-C. Duluc, D. Juric, F. Feuillebois, N. Périnet, G. Prigent, A.-H. Ebo Adou, B. Xu, L. Kahouadji, with contributions of V. Daru (AERO), J. Chergui (CIGITA), O. Le Maître (AERO), P. Le Quéré (CORO)

In the broad field of two-phase flows, LIMSI claims its experience in numerical techniques for simulating the dynamics of interfaces. The techniques used depend on the case under consideration. For suspensions of particles, droplets or bubbles, the characteristic length of the interface is much smaller than that of the fluid flow. In such conditions, the shape of the interface hardly changes, and drops or incompressible bubbles can be treated like particles. In addition, microscopic situations make inertial effects much less preeminent. Microscale phenomena are thus approached with analytical or asymptotic methods. At usual scales, the fluid and the interface have similar sizes. Moreover, the interface can take special shapes, like in Faraday waves for instance. For such cases, we follow the evolution of the interface shape with the Front-tracking technique. Faraday waves are very interesting theoretically while being useful for checking the validity of our numerical schemes by comparing our results to experimental data. A significant effort was made in these last years in parallelizing the numerical code handling gas phases with constant and uniform density, a task achieved with the significant contribution of J. Chergui (CIGITA). We also remember that LIMSI’s long term goal is to accurately simulate liquid-vapor flows involving phase change, heat transfer and convection. In this third kind of issues, bubbles may grow by evaporation, detach, shrink, coalesce, etc., so that the effects of gas-phase compressibility must be taken into account. By using the Low Mach number approach, compressibility effects were included into our numerical codes while still ensuring mass conservation. We could thus study the dynamics of vapor bubbles in microscale geometries. Obviously, there is still much to do, for instance describing the dynamics of the contact line with solid surfaces when relevant, or including the heat and mass transfers related to phase change.

Suspensions and droplets

Solid suspensions in micro-scale flows are studied in collaboration with PMMH, LadHyX, École Polytechnique de Tunisie, IPPT at the Polish Academy of Science (Warsaw, Poland), Univ. Warsaw (Poland), Zhukovskiy Inst. (Moscow region, Russia), Inst. Physical Chemistry and Electrochemistry at the Russian Academy of Science (Moscow), and MIT (USA). At micro-scales, the Reynolds number $Re$ is much smaller than 1 and the dynamics of solid suspensions is mainly ruled by hydrodynamic interactions with walls. Small inertial effects in the fluid (of the order of $Re^2$) produce differential lift forces on the particles, thus inducing particle separation. Those lift forces can be derived by a perturbation method. For a particle in a shear flow close to a wall, the perturbation problem is regular; the lift force on a spherical particle contains various coupling terms that we use for modeling separation processes (Yahiaoui and Feuillebois 2010). For two particles in an unbounded shear flow, the singular perturbation problem is solved by matching asymptotic expansions. The flow fields and the resulting particle velocities depend on the relative positions of the two wakes (Asmolov and Feuillebois 2010). We have also established solutions (at the order of $Re$) in creeping flows for various combinations of walls and particles. The case of spherical particles in a Poiseuille flow along a solid plane walls was solved with an analytical method, see Illustration 1, and results were effectively used for optimizing separation techniques in analytical chemistry (Pasol et al. 2011).

Illustration 1: Velocity of a freely moving sphere carried by a Poiseuille flow (normalized by the maximum Poiseuille flow velocity) as a function of the dimensionless sphere radius $\alpha$ and the dimensionless sphere center position $s$. The Stokes equations for the creeping flow were solved by the multipole method which is very accurate (Pasol et al., 2011).

That basic case was extended to more and more complex shapes of the particles and the walls: e.g. ellipsoids settling in a cubic container -solved by the boundary integral method (Hedhili et al. CMES 2011)-
or spherocylinders (trunk of a cylinder and two hemispherical caps) as used in biological applications. The multipoles, where the spherocylinders were modeled as assemblies of interpenetrating spheres, again lead to excellent agreements with experiments (Mongrul et al. 2011). When the walls are porous (with pores much smaller than the particles), the difficulty lies in the boundary conditions between the fluid and the porous wall, where the Stokes and Darcy equations apply respectively. A first approach, based on singularities in the Stokes flow close to a porous membrane, relies on the fundamental solution where singularities are located outside of the flow field. In a first step, no-slip conditions were assumed along the porous wall (Debbiche et al. 2010). The more elaborate Beavers and Joseph slip-conditions were used in following works. The case of several particles in a viscous flow near a porous wall was treated, first by a perturbation method developed at the fourth order with respect to the ratio $D_{\text{pore}} / D_{\text{particle}}$ (Khabthani et al. 2011), then with a peculiar semi-analytical boundary integral technique adapted to the slip boundary condition on the porous wall. The special case of a single spherical particle was solved analytically by the method of bi-spherical coordinates (Feuillebois et al. AIP Proc., 2011). Hydrophobic or super-hydrophobic walls, well-represented by slip conditions, can be used for inducing mixing in microscale flows. F. Feuillebois rigorously proved that the wall textures can be optimized in order to maximize the cross-flow in the spanwise direction and thus the mixing effect (Feuillebois et al. Phys. Rev. E 2010).

In the case of severe accidents, Pressurized Water Reactors are sprayed with water droplets. Nuclear engineering thus needs to better know the dynamics and thermal effects of droplets. We studied how the two water droplets coalesce during their fall from the injection nozzles which are located at the top of the containment vessel. We have shown that the various collision regimes, as measured at IRSN-Saclay, are well correlated with a new “symmetric Weber number” (Rabe et al 2010). Droplets are also important in aircraft engineering; for instance icing of aircrafts due to impinging supercooled water drops is likely to cause severe accidents. We calculated freezing of supercooled drops in airflow with the method of matched asymptotic expansions based on the Stefan number (Tabakova et al. 2010) and found that when a liquid drop hits a dry solid surface, an axisymmetrical jet is ejected from the wall. The shape and dynamics of such jets were calculated by solving the unsteady boundary layer at the second order, accounting for the presence of the free surface (Tabakova et al. 2011). The results agree well with recent experimental observations using rapid video pictures of drops in icing wind tunnels (Mongrul et al. 2011).

F. Feuillebois, now retired, was honored by an international symposium dedicated to his 65th birthday.

**LARGE SCALE LIQUID–GAS INTERFACE WITH INCOMPRESSIBLE GAS PHASE – PARALLEL DNS IN 3 DIMENSIONS**

One trump of LIMSI’s in the field of numerical simulations of two-phase flows is the *Front-tracking* technique. We apply this technique to flows where the gas phase is either incompressible or weakly compressible.

D. Juric, J. Chergui (CIGITA LIMSI) and S. Shin (Hongik Univ.) have developed the high performance, parallel code BLUE. BLUE is based on a high fidelity hybrid Front-Tracking/Level-Set algorithm for the Lagrangian tracking of arbitrarily deformable phase interfaces and a precise treatment of surface tension forces, interface advection and mass conservation. BLUE couples an implicit, 3D incompressible Navier-Stokes solver with multigrid pressure solution to the Lagrangian tracking method for implementation on large-scale parallel computing architectures. Validation tests have been performed on LIMSI’s parallel cluster (196 cores). On massively parallel machines (IBM BlueGene/Q machines), BLUE has shown excellent scalability performance up to 8192 processors at IDRIS, see Illustration 2, and up to 16384 processors at the Julich Supercomputing Center in Germany (ranked world’s fifth fastest supercomputer).

The modular program structure allows for the application of the code to a wide variety of physical scenarios: free surface instabilities, flow of bubbles or drops with coalescence and breakup, droplet impact or flow around immersed solid objects for microchannel flows for example. We focus our studies on physical phenomena of large spatio-temporal extent where high performance is indispensable. One example is the canonical phenomenon of a high impact water droplet splash onto a film of water (see Illustration 3). Other projects involve recent experiments by J. Rajchenbach (Univ. Nice) of highly nonlinear Faraday waves which show five-petaled localized patterns that have never been observed previously. Simulations by A. Ebo Adou have reproduced the experimental pentagonal pattern in this regime. Another set of Faraday experiments, conducted by Y. Couder’s group (Univ. Paris-Diderot), demonstrates exotic petal like patterns on the surface of a rotating vibrated liquid surface. Work with L. Kahouadji and L. Tuckerman (PMNH-ESPCI, Paris) is aimed at characterizing the instability threshold of this rotating Faraday experiment. N. Périer (Univ. Chile) is conducting simulations using BLUE on an IBM iDataplex cluster at Univ. Chile in a study of the dynamics and interactions of solitons in a hydrodynamic channel. The PhD work of B. Xu (LIMSI and FAST) on simulation and scaling of two-phase microfluidic flows is inspired by the recent discovery by T. CUBAUD (Stony Brook Univ., New York) of a remarkable new
class of two-phase flow morphologies involving thin miscible and immiscible viscous threads in microfluidic devices.

Our program on the study of the dynamics of free surfaces, films and general fluid-fluid interfaces can find applications in a wide variety of situations such as free-surface waves and turbulence, jets, bubbles and drops. The engineering applications range from microfluidics (e.g. micro-encapsulation) to marine engineering (ocean waves, hull drag reduction by bubble injection) and chemical or bio-engineering processes at scales in between. The code BLUE can be adapted to problems involving phase change or flame fronts.

Illustration 2: BLUE's performance increase with number of cores: linear speedup up to 8192 processors on the IBM Bluegene at IDRIS, Orsay

Illustration 3: A water drop splashes onto a free-surface of water Sequence of 6 snapshots. Parallel 3D simulation on 4096 cores at JSC, Germany.

MICROFLUIDICS WITH A COMPRESSIBLE GAS PHASE

Two-phase flows involving phase change cannot be completely simulated without accounting for the equation of state of the gas phase and the compressible nature. However, when the fluid velocity is much slower than the sound speed, e.g. in configurations which are mainly controlled by heat transfer, significant reduction in CPU time can be achieved thanks to the Low Mach Number approximation. V. Daru (AERO group) developed efficient numerical schemes where one phase follows the Low Mach Number approximation and the other one is divergence-free. The concept of a dual fluid (one phase weakly compressible, one phase incompressible) is valid as demonstrated by 1D test-cases involving liquid-vapor phase change and fast interface dynamics (Duluc et al. Microfluidics & Nanofluidics 2009). However, two issues were to be addressed before simulating 2D or 3D configurations. First, the thermodynamic pressure in the gas phase must be connected to the pressure field in the liquid phase although the latter is defined up to an additive constant. For instance, consider a contiguous liquid phase, not submitted to gravity, containing several gas bubbles where the gas pressure takes different values from one bubble to the next. The forces exerted by the bubbles on the liquid generate motion in the liquid phase, then the fluid inertia induces alternate expansions and contractions of the bubbles. The solution developed by V. Daru in the AERO group ensures continuity of the total pressure field by introducing the extended pressure field in the algorithm (Daru et al. JCP, 2010). See more numerical details in the section of the AERO group.

The second concern is exact mass preservation by the front-tracking algorithm when the flow is divergence-free on one side only of the interface. This is a crucial, delicate and very demanding issue. G. Prigent’s made great progress on this point during his PhD thesis. He rigorously verified each step of the numerical scheme, and then replaced the smooth Heaviside function used in the front-tracking technique by a sharp stepwise one. Discrepancies in the mass and energy balances were reduced down to acceptable values while the algorithm is robust and rapid. Now, our code can be used for simulating isobaric flows where a gas bubble expands or contracts, as well as isochoric flows, where the thermodynamic pressure in the bubble may fluctuate. A new test-case at low velocity has been elaborated where a gaseous bubble is transported by water across a non-isothermal micro-channel (Prigent et al. ASME 2012), see Illustration 4. The stepwise temperature change on the walls induces a delayed pressure change.

increase in the bubble, as represented in Illustration 5. Because of such compressibility effects, gas bubbles could be used as actuators in microfluidic applications.

It can also be seen that any new version of our numerical codes is validated by comparison with either analytical solutions, numerical solutions given by other physically relevant models, data derived from linear stability analyses, or experimental data when possible. This rigorous approach requires significant effort, but we meanwhile elaborate original test-cases that can be helpful as benchmarks proposed to the two-phase flow community.

Illustration 4: An isochoric air bubble flows through a water filled micro-channel; the stepwise temperature change is supplied at the walls. The picture shows alteration of the temperature field induced by the bubble crossing.

Illustration 5: Pressure change undergone by an air-filled bubble flowing in a micro-channel filled with water, the wall temperature of which is a stepwise function. Grid-convergence and comparison with the analytical solution of heat-diffusion only.

TOPIC 2: OSCILLATING FLOWS, DYNAMICS AND TRANSFERS

S. Kouidri, D. Bâltean-Carlès, F. Jebali Jerbi, G. Defresne, R. Paridaens, Ph. Debesse, with contributions of V. Daru (AERO), and F. Lusseyran (AERO)

In LIMSI, a research activity that involves people of different groups is called transverse, and when it is perennial enough then it appears in the organizational chart as a Transverse Action. So it is for the Transverse Action Thermoacoustics-Cryogenics, to which people of the three groups contribute. It was decided to present the numerical activities based on the Navier-Stokes equations in the CORO group, while the TSF group rather deals with experimental investigations on a full-size machine.

Like many other laboratories involved in thermoacoustics, LIMSI focuses attention on the acoustic streaming, both experimentally and numerically. As explained before, only the former aspect is presented here-under. Acoustic streaming is the generic name of secondary flows (their velocity is one order of magnitude less than the acoustic velocity) which are generated within acoustic waves developed in 3D geometries with no-slip conditions at the walls, such as thermoacoustic stacks, acoustic loops of Stirling-type thermoacoustic machines, or simple resonator tubes. The acoustic streaming does not consume much acoustic energy but it induces enthalpy transfers which are very unfavorable to the efficiency of thermoacoustic machines. That phenomenon thus deserves deep studies. With the precious help of F. Lusseyran (AERO group), several experimental techniques have been developed in the Solid-Fluid Transfer group : characterization of the secondary velocity field, either by Particle Image Velocimetry (PIV) or by Laser Doppler Velocimetry (LDV), characterization of the secondary pressure field related to the secondary flow.

The LIMSI’s thermoacoustic prime mover consists of a linear resonator coupled to an annular loop (4.25m long Stirling-type engine with progressive waves at 22Hz in nitrogen gas at pressures up to 30bars), cf. Illustration 6. It is equipped with piezoelectric pressure sensors and with a Laser Doppler Velocimetry (LDV) apparatus, see Illustration 7. Analysis of the experimental pressure profiles demonstrates that the acoustic field can be correctly described by a linear model, see Illustration 8 (Kouidri et al. CFA 2010, ASME-ATI-UIT 2010; Paridaens et al. CFM 2011, ASME 2011). It can also be deduced that both Mach number $M$ and nonlinear Reynolds number $Re_{NL}$ are low [$Re_{NL} = (M R/\alpha)^2$], where $R$ the radius of the
resonator and $\delta$ the thickness of the viscous boundary layer]. Further analysis then leads to the secondary pressure field and shows that the acoustic streaming flow is of the slow-type (linear regime). We have then developed an analytical mode based on successive approximations and asymptotic developments (Paridaens et al. Acoustics 2012). The calculated velocity profiles compare favorably with the experimental data of the axial acoustic velocity $U_a$ and of the second order velocity $U_m$ (acoustic streaming) despite deviations in the vicinity of the wall, see Illustration 9.

Illustration 6: LIMSI’s Thermoacoustic prime mover.

Illustration 7: The LDV equipment and the measurement window implemented on the resonator. The position is indicated in Illustration 6.

Illustration 8: Experimental and numerical values (resp. dots and lines) of the acoustic part of the pressure field along the resonator and loop; the positions of the piezoelectric sensors are given in Illustration 6.

Illustration 9: Velocity profiles of the first and second orders (vs. radial position, resp. above and under): measured and calculated data for three heating power-rates (resp. 165, 190, and 210W) with a mean pressure of 10 bars.

Moreover, the model evidences various contributions to the generation of the acoustic streaming: the viscous stress ($\phi_1$), the Reynolds stress ($\phi_2$ and $\phi_3$) and the acoustic flow ($\phi_4$). Illustration 10 shows the respective contributions for one experimental configuration. The collaboration with Prime (Poitiers) in the framework of the GdR 3058 Thermoacoustique (Task Investigation of streaming flows by laser metrology) was very useful for sharing skills and comparing the results of LDV measurements.
**TOPIC 3: HEAT TRANSFER FROM SOLID TO SUPERFLUID HELIUM**

**J. Amrit, A. Ramière, V. Radha Krishnan, Q. Li**

This theme focuses research on heat-transfer at cryogenic interfaces and heat-transport in micro/nano-structures. Three issues are investigated simultaneously, namely (1) the thermal boundary Kapitza resistance at Silicon crystal/superfluid Helium interfaces, (2) the thermo-magnetic stability of superconducting cavities (SC) for particle accelerators and (3) the thermal transport in nanowires and micro/nano-junctions. Our studies mainly rely on experiments conducted at low temperatures, which are complemented with theoretical and numerical work. The underlying physical phenomena of interest are the scattering of energy carriers (phonons) at interfaces and boundaries, and the resulting dissipation.

The thermal boundary resistance (Kapitza resistance, *i.e.* a finite temperature jump at interfaces) is studied in collaboration with IPNO (Orsay). We measured the resistance between a highly polished single-crystal Silicon (111) and superfluid Helium at temperatures as low as 0.4-2.1K. This premiere was possible thanks to the unique cell geometry designed for our experiments (Amrit & Thermeau *J. Phys.* 2009). Analysis of the results evidenced a transition in the transmission process: due to the nanometer size of surface roughness, scattering changes from diffuse to specular when temperature decreases. It was the first time that this transition was described (Amrit *Phys. Rev. B* 2010). Current studies investigate the thermal boundary resistance as a function of the acoustic impedance (density x speed-of-sound) of superfluid helium. The measurements are conducted from atmospheric pressure to 23 bars. The resulting change by 80% in the acoustic impedance induces a change of 7% only in the thermal boundary resistance; see Illustration 11 (Ramière *et al.* 2012 and 2013). These results confirm that tailoring of interface transmission requires a control of the interface roughness. Current experiments examine the transition in the thermal boundary resistance at the Si/He interface upon solidification of superfluid Helium.

![Illustration 11](image)

*Illustration 11:* (a) Kapitza resistance at the Si/He interface as a function of pressure at two temperatures. (b) Kapitza resistance at the interface Si/He under atmospheric pressure as a function of temperature and the experimental cell (insert). (c) Nanometer scale surface roughness (squares) required to interpret data and roughness-to-wavelength ratio (diamonds) characterizing the nature of scattering.

The studies on the thermal stability of superconducting cavities (SC) of particle accelerators are conducted in collaboration with C.-Z. Antoine (CEA/Saclay/Ifé). We measured the Kapitza resistance between Niobium single crystals and superfluid He. The samples were supplied by the *Fermi National Accelerator Laboratory* (Illinois USA) and were characterized at ICMO (Orsay). The data, that complement our previous measurements and numerical simulations on polycrystalline Niobium (Amrit & Li 2008), were recently used for the first time in view of a novel design for accelerator cavities made of Nb single crystals (Amrit and Antoine 2010). The data also gave access to the influence of surface defects on the Kapitza resistance (Amrit & Ramière 2013 idem). All these results constitute a benchmark for the conception of SC. Current numerical simulations focus on the occurrence of hotspots on SC during their operation.

Studies on the thermal transport in nanowires and micro/nano-junctions have been conducted in a joint research collaboration with S. Volz (EM2C, École Centrale Paris) for over six years. In 2010 we extended...
our partnership to F. Parrain (IEF Orsay) and O. Bourgeois (Institut Louis Néel, Grenoble). These two collaborators take in charge the fabrication of samples (MEMS devices) and detectors (nanofilms). Venkatesh Radha Krishnan, financed by a one-year post-doctorate grant of the PRES UniverSud, investigated the electronic ballistic heat transport in metallic nanowires and the role of the thermal boundary resistance between the nanowire and its substrates, as a function of the nanowire diameter (Venkatesh et al. 2011). Currently and as part of the PhD work of A. Ramière, thermal transport in the ballistic regime across micro junctions is studied. The aim is to demonstrate new physical laws describing the energy dissipation in micro- or nano-electronic systems at ambient temperatures. Experiments are done at low temperatures (below 2K) where the ballistic regime is fully established. Monte Carlo simulations for thermal transport at micro-scales are also performed\(^4\), see Illustration 12. This work is supported by the LabEx LaSIPS, Paris-Saclay.

Simultaneously, we also examine the effects of turbulence on the heat transfer coefficient in a cryogenic heat exchanger, which was specially designed and built for this study (Amrit et al. EJP 2012). Current and future research shall focus on thermal phenomena at micro/nano-scale related to surface roughness and size (geometry) change, an issue which is very active internationally.

Illustration 12: Thermal conductance in mesoscopic silicon ribbons at low temperatures, our Monte Carlo simulations for different values of the surface roughness (dashed lines) and the experimental results of Héron et al. (Nano Letters, 9, 1861, 2009) (dots). Note the departure from the behaviour in \( T^3 \).

TOPIC 4 : APPLIED CONVECTIVE TRANSFERS

M. Pons, V. Bourdin, M.-C. Duluc, M. Jarrahi, G. Defresne, M. Firdaouss, E. Tapachès, S. Wullens, M. Chhay

The applications of convective transfers we are interested in are connected to some issues related with energy concerns. For instance, we study the effect of heat-flux modulation on external free convection because we expect the heat-transfer to be intensified, or we study natural ventilation of buildings because we expect energy savings via a reduced use of air-conditioners. Lastly, the TSF group contributes to the general effort for promoting renewable energies, namely solar energy : solar air-conditioning, concentrated solar power in tropical islands, and low concentration for photovoltaic panels.

ENHANCEMENT OF EXTERNAL FREE CONVECTION

Free convection around a line source has been investigated for long in our group : a horizontal metallic wire immersed in a pool of fluid was submitted to a stepwise electrical heating. Heat-flux modulation may result in non-linear effects or thermo-convective instabilities, thus leading to enhancement in heat-transfer. M.C. Duluc and M. Jarrahi (who recently joined LIMSI as an assistant professor in the IUT d’Orsay) build a new experimental set-up for studying the fundaments of those interactions. The wire can now be heated with a modulated power-rate. After validation of the instrumentation and experimental procedures, measurement campaigns have now started, see Illustration 13. Moreover PIV measurements planned in a second step will give insight on the flow patterns around the wire and will permit comparison with numerical simulations. The long term concern is about the most efficient geometries and modulations for heat-transfer intensification.

NATURAL VENTILATION IN BUILDINGS

The wide development of air-conditioning raises serious energy issues. Nocturnal ventilation offers free-cooling at night, and thus can reduce the use of air-conditioners. The design of an efficient ventilation system requires reliable numerical simulations of air flows in buildings but such simulations are very challenging, because the effective Reynolds and Rayleigh numbers are very large, because the real houses or flats are geometrically complex, and because simulations must be done over very long periods. We entered the subject via the ADNBATI project (Amélioration de la Description Numérique du BÂTI, Programme Energie of CNRS) in collaboration with PIMENT (Univ. La Réunion) and LOCIE-INES. The first purpose was to compare the various methods currently used for computing the heat-transfer induced by natural convection in a room with two opposite openings. The results demonstrated the need of advanced CFD computations, see Illustration 14 (Pons et al. ACOMEN Conf. 2011). However, a real building involves many coupled phenomena such as solar fluxes, wind fluctuations, radiation, conduction and inertia in the walls, humid air, composite materials, without forgetting the interactions with the occupants. During his post-doc co-financed by LIMSI and LOCIE-INES, M. Chhay evaluated the possibilities of addressing such issues with multi-level simulation (Pons et al. SFT Conf. 2011). However, the rapid development of HPC made us turn toward coupling CFD and zonal models onto a co-simulation platform. The fluid convection is handled by CFD while wide-range interactions and slow phenomena are handled by the zonal models presently used by the consultants in building energetics engineering. S. Wullens, PhD student co-directed with E. Wurtz (formerly LOCIE, currently CEA-INES) and financed by the 4C ANR project (coordinated by PIMENT) began in 2010 implementation of pressure-based boundary-conditions for open domains into one LIMSI’s code (OLORIN). He first investigated the ADNBATI case (single room with two openings), so confirming the results obtained by PIMENT, see Illustration 15 and (Wullens et al. SFT 2013). He also validated his work with the data of the “vertical chimney” benchmark conducted by Chenier et al. in the framework the French community on Thermal Sciences (SFT), see the section Buoyant convection modeling, Topic 1 in CORO group. He is now implementing the coupling of the CFD code with a multizone model (Modelica framework, CEA-INES) onto a test platform using the ‘cloud’ recently opened by CNRS. The purpose is to simulate the behavior of a simple whole building in transient conditions. This will be a significant contribution to an on-coming co-simulation platform devoted to building simulations.

A significant feature of the natural flow in the ADNBATI room is the presence of two large recirculation cells that occupy almost all the volume, see Illustration 15. In collaboration with M. Hasnaoui (Univ. Marrakech), M. Firdaouss conducted a more academic study: 2D square cavity heated from below, with a model based on the stream function-vorticity formulation. The configuration with two horizontal cells is intrinsic to that configuration, see the BHF case in Illustration 16. This study also showed that the two-cell flow unfortunately reduces heat-transfer compared to other configurations (Raji et al. 2012). Investigation must be continued toward other aspect ratios and larger values of Ra.
**Solar Energy**

Historically, some members of the TSF group were involved in solar-powered refrigeration. It was then logical for M. Pons to contribute to the ANR project *Orasol*, the aim of which was to compare on a sound basis the performance of six solar-powered air-conditioners of various sizes, based on four different principles (liquid or solid sorption, continuous or discontinuous cycles, closed or open cycles), and tested in five different places (from La Rochelle on the Atlantic coast to the tropical island La Réunion). The thermodynamic approach is based on non-dimensional energy- and mass-fluxes in order to describe the energetic behavior of the units, from incident solar energy to cold production. The analysis included the heat rejected to the atmosphere, the electricity consumed by auxiliaries, and the water consumption when relevant. Thanks to that analysis, comparison between the performance recorded during two years gives comprehensive insight on various features such as possible degradation of performance, or quantitative differences between continuous cycles (liquid sorption or rotary desiccant wheel) and discontinuous ones (solid sorption). Special attention was devoted to statistics on the actual electricity consumption of the tested solar air-conditioners. This point is usually neglected in the literature although its reduction is expected to be the main environmental benefit of that technique. The *Orasol* study demonstrates that the initial design of the system through which heat is rejected to the atmosphere is extremely important (Pons et al. *Energy* 2012). The exergy analysis of solar-powered was also developed in the framework of the *Orasol* project. As a first step, was established the method for evaluating the exergy content of solar radiation at the terrestrial level (Pons *ECOS Conf.* 2008 & 2011) or when the ambient temperature changes (Pons *IJoT* 2009). Applying then that method to actual data collected in Odeillo (PROMES) and in La Réunion (PIMENT) gives access to the exergy losses which are specific to given uses of solar energy: with flat-plate collectors (without concentration) or with huge fields of heliostats (quasi-infinite concentration), for producing heat, possibly converted into electricity, or for photovoltaic conversion (Pons *Renewable Energy* 2012).

From the *Orasol* study, it sounded logical to extend our interest in solar energy in two directions. Both are related to relatively low concentration, which is intermediate between no-concentration and infinite concentration. The first study involves photovoltaic conversion and is conducted in strong collaboration with LGEP (Orsay, LabEx LaSIPS). Since 2011, V. Bourdin (TSF group), A. Migan and J.P. Kleider (LGEP) investigate the benefit of using simple mirrors for enhancing the electricity produced by photovoltaic panels. Two experimental campaigns have been conducted in summers 2012 and 2013, see the experimental field Illustration 17. Compared to reference panels, the panels equipped with mirrors exhibit experimental performance (under nominal insolation) enhanced by 18% for poly-crystalline cells and by 29% for amorphous cells. Such a result is very encouraging, and current studies focus on thermal effects and mirror optimization. The second concern is production of electricity by an Organic Rankine Cycle powered a Fresnel-type concentrating solar collector. This is an extension of our collaboration with PIMENT. Indeed, due to a specific energetic context (significant cost of the fuel imported for producing electricity), a tropical island like La Réunion is interested in Organic Rankine Cycle (ORC) powered by Concentrated Solar Power (CSP). The PhD thesis started in 2012 (E. Tapachés, in co-direction with F. Lucas at PIMENT) first developed an efficient algorithm for using the Monte-Carlo software EDSTAR that calculate the flux absorbed in the visible wavelengths after reflection on various surfaces (mirrors, like in...
the former case, and possible secondary reflector). On both studies, we are now working on coupling the radiative fluxes (short and long wavelengths) and the convective-conductive transfers. This will open the way for later optimization.

Illustration 16: Flow-pattern phase-diagram in 2D square cavity heated from below. The mono-cellular flow pattern (MF, closed squares), which is the fundamental mode for this geometry, may exist up to \( Ra=2.5 \times 10^6 \). Beyond this value, only the horizontal two-cell flow (BHF, open triangles) exists. Note that the transition between the MF and BHF flows displays an hysteresis. Also note the low Nusselt numbers for the BHF flow.

**Highlights**

- Development of a massively parallel numerical code for incompressible two-phase flows using the front tracking technique (BLUE).
- Pentagonal quasi-crystal pattern for Faraday waves calculated for the first time, in good agreement with experimental observations, thanks to BLUE. Moreover, calculation of an exotic regime of hexagonal patterns in Faraday waves (heteroclinic cycle alternating between quasi-hexagonal and beaded stripe patterns)
- For the first time, measurements of the Kapitza resistance between a single-crystal of Silicon and superfluid Helium at temperatures as low as 0.4K, and also with a pressure of the superfluid Helium ranging from Standard Vapor Pressure to 25 bars (various temperatures).
- Excellent agreement between numerical simulations and experiments for the jet occurring after the fall of a liquid drop on a solid surface.
- Numerical methods for simulating discontinuous compressible gas phase enclosed in a liquid volume (with AERO group).
- Development of pressure controlled boundary conditions for open domains (with CORO group).
## STAFF

### PERMANENT STAFF

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### PHD STUDENTS

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### INTERNSHIPS

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INDICATORS OF SCIENTIFIC NOTORIETY

EDITORIAL BOARD APPOINTMENT


ORGANIZATION OF INTERNATIONAL OR NATIONAL SCIENTIFIC EVENTS (ACADEMIC)

**MEMBER OF THE SCIENTIFIC, TECHNICAL PROGRAM AND/OR ORGANIZATIONAL COMMITTEES FOR INTERNATIONAL/NATIONAL CONFERENCES OR WORKSHOPS**

- D. Baltean-Carlès and S. Kouidri were members of both organizing and scientific committees of the first summer school on *Thermoacoustics*, endorsed by CNRS, held in Roscoff, May 30-June 4, 2010 (42 participants).
- Scientific committees:
  - S. Kouidri for the 26th *IAHR Symposium on Hydraulic Machinery and Systems* (Beijing China, August 19–23, 2012).
  - S. Kouidri for the 5th International Symposium on Fluid Machinery and Fluids Engineering (Jeju, Korea October, 24-27 2012).
  - M. Pons for the conferences of IBPSA-France (Int. Building Performance Simulation and Analysis) and for the first Spring-school *SIMUREX* (as President) endorsed by CNRS (IES Cargèse, April 18-24, 2010).

**INVITED LECTURES, TALKS OR SEMINARS**

**KEYNOTE SPEAKER AT AN INTERNATIONAL CONFERENCE**


**TUTORIAL AT WORKSHOPS OR CONFERENCES OR SUMMER SCHOOLS**

- D. Baltean-Carlès, A thermoacoustic prime-mover prototype, lab class at the 1st *summer school on Thermoacoustics*, Roscoff, May 30-June 4, 2010.

**INVITED TALK (NATIONAL OR INTERNATIONAL)**


• M. Pons, Second-law analysis of adsorption cycles, invited lecture at Kyushu University (Fukuoka, Japan) Dept Mechanics Energetics (January 22-24, 2013).

**Participation in expertise and administration of research**

**International or national scientific networking**

**International networks**

• PICS French-Polish cooperative agreement between CNRS and IPPT, Polish Academy of Sciences, on Hydrodynamic interactions in suspensions (2009-2011) : F. Feuillebois.

• Cooperative agreement N° 23897 between CNRS and Bulgarian Academy of Sciences, on Freezing of a flowing liquid film and application to icing (2010-2011) : F. Feuillebois.

• French-Algerian collaboration in the CMEP program 10MDU809 (P. Le Quéré director) on *A numerical and experimental study of thermoacoustic systems* (2010-2014), within the framework of the Hubert Curien Tassili program : D. Baltean-Carlès.

**National networks or working groups**

• Fédération TM&C (Transferts de Masse et de Chaleur Ile-de-France) : J. Amrit, M. Pons

• European GdRe Thermal Nanosciences and Nanoengineering (S. Volz EM2C) : J. Amrit.


• PRES-Universud : J. Amrit.

• GdR CNRS No 3058 Thermoacoustique : D. Baltean-Carlès, F. Jebali Jerbi, S. Kouidri, and M. Pons.

**Participation in evaluation or expertise committees**

**National committees (CoNRS, CNU, CCSU...)**


• CCSU 60 of UPMC 2008-2011 : D. Baltean and M. Pons.

• CCSU 60 of INPL Nancy 2009-2012 : M. Firdaouss.

• CCSU 60-62 of Univ. Paris-Est Marne-la-Vallée 2010-2011 : M.-C. Duluc.

• CCSU 60-62 of UJF Genoble 2009 : M.-C. Duluc.

• CCSU 60-62 of Arts et Métiers ParisTech 2010-2012 : S. Kouidri

**Expert for scientific evaluation committees**

• Scientific evaluation for Ministère de l’Enseignement Supérieur et de la Recherche, Crédit Impôt Recherche : S. Kouidri.

• Scientific Committee of Laboratoire National de Métrologie et d’Essais : S. Kouidri.

**Member of selection juries**

• Juries of HDR thesis defenses (2 x M. Pons)

• Juries of the Agrégation Mécanique (M.-C. Duluc from 2009 to 2013)

• Juries of PhD thesis defenses (2 x D. Baltean-Carlès; 1 x M.-C. Duluc; 10 x S. Kouidri; 1 x J. Amrit; 6 x M. Pons)

• Selection juries of U-PSUD, IUT-Cachan, IUT Orsay, IUT –Evry : J. Amrit

**Teaching activities and duties in relation to research**

**University Paris-Sud**

• Master PAM (DFE + PIE) : Coordination of the module Énergies Renouvelables et Efficacité Énergétique plus course in Énergie Solaire, V. Bourdin.

• Master DFE : Ventilation et Composants (in Thermique du Bâtiment), M. Pons.
**University Pierre et Marie Curie**

- Master Mechanics: Suspensions and two-phase media, F. Feuillebois.
- Master Mécanique des Fluides: (i) Internal Flow in Turbomachinery; (ii) Aeroacoustics and Noise Pollution (in common with Arts & Métiers Paristech), S. Kouidri.
- Master OMEBA: Solar-Powered Refrigeration, M. Pons.

**University Paris-Diderot**

- Master Ingénierie et Physique des Énergies: (i) Forced convection; (ii) Pool boiling, M.-C. Duluc.
- Master Ingénierie et Physique des Énergies: (i) Desiccant cooling; (ii) Radiative Heat Transfer; (iii) Natural Convection, M. Pons.

**Foreign Universities**


**Research conventions and contracts**

**Academic partnerships**

- Institut Physique Nucléaire d’Orsay (J.-P. Thermeau, F. Chatelet, F. Dubois), Résistance de Kapitza
- CEA, Irfu/Saclay (C. Z. Antoine), Cavités supraconductrices.
- IEF, Orsay (F. Parrain, A. Bosseboeuf), Fabrication des dispositifs de type MEMS.
- Institut Néel, Grenoble (. Bourgeois), nanofabrication depuis 2010.

**Industrial relationships**

- CEA, 2010, Building Simulation and Analysis program, M. Pons.
- ALTRAN RESEARCH (informally), 2012, Optical and thermal model for simulation of PV panel, V. Bourdin.
# Table of contracts for TSF group

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## Scientific Publications

### Doctoral theses and HDR


### Articles in peer reviewed scientific journals


Books & Chapters in Books

34. Pons, M. Méthode pour analyses exergétiques robustes d’installations solaires et de bâtiments. in International Building Performance Simulation Association Conference. 2008. Lyon, France. 8p.
42. Prigent, G., M.-C. Duluc, and P. Le Quéré. Pressure and volume changes of a gas bubble entrained in a liquid ow through a heated microchannel. in European Thermal Science Conference. 2012. Poitiers, France. 8p.


CONFERENCES WITHOUT PROCEEDINGS, WORKSHOPS


