Heat and mass fluxes across a density interfaces submitted to a grid-generated turbulence

Pascal DUPONT[1&2] et Hassan PEERHOSSAINI[2]

[1]LGCGM, EA3913, INSA de Rennes, Campus Beaulieu, 35043 Rennes cedex
[2]Thermocinétique, UMR6607, Polytech'Nantes, BP 50609, 44306 Nantes cedex
email: pascal.dupont@insa-rennes.fr

Abtract :

The present study was first motivated by the industrial problem of the Liquefied Natural Gaz storage tank where the stratification between two different LNG layers could be destroyed by the increasing unstable thermal stratification. Then the choice was to reproduce the historical experiments of Turner with a thin stratified interface separating two homogeneous media mixed by oscillating grids. Comparisons between thermally or salinity stratified experiments exhibit the strong dependence of the flux on the molecular diffusivity.
A phenomenological model is proposed for these transfer with a clear serial scheme which is different from the previous parallel ones. It gives a clear understanding of the influence of the molecular diffusivity on the flux across those density interfaces.

Résumé :

La présence d'une stratification stable en densité modifie profondément l'évolution des cuves de stockage de Gaz Naturel Liquéfié en inhibant les mouvements verticaux et les transferts de chaleur et de masse induits. Nous avons simplifié l'étude en considérant le cas d'une interface fine séparant deux milieux homogènes agités par une turbulence de grille oscillante. Les résultats expérimentaux sont présentés de manière à mettre en exergue l'influence du coefficient de diffusion moléculaire et à proposer un modèle phénoménologique d'évolution de ces stratifications.

Key-words : Heat and mass transfer ; stratified medium ; thermo-haline interface

1 Introduction

Stratification of fluid medium arose spontaneously either because of the large scale involved as in geophysical case, or because of the relatively large density gradient in the industrial case. The various fluid motions mix partially the medium that is constituted by well-mixed layer separated by interfaces where the density varies rapidly. The most studied situation is that of the double-diffusive natural convection where the flow in induces by the destabilising flux of heat. In that case, Turner have performed the first and still used database of the fluxes against the interface density ratio R_ρ. Linden (1974) have proposed a model of transfer, in which the fluxes by diffusion and entrainment operate in parallel. The total buoyancy flux is then the sum of two fluxes, and the entrainment flux was based on an empirical equation deduced from the results of Turner (1968), in the case of a salt stratification. Harinda and Fernando (1989) proposed a complex model phenomenological, in which they supposed that the interface has two boundary layers: one thermal and the other salt (as Veronis). Considering that the key point is the flux of the stratifying property in relation to the energy either potential with a destabilising gradient or mechanical with an external flow, Zellouf et al. (2005) have presented new and accurate results of the flux of a single property across density interfaces in a grid-generated turbulence. This forced convection case was already performed by Turner (1968) who has described for the first time the important influence of molecular diffusivity. Turner have made an attempt to predict the relation between the flux and the Peclet number that gives the general philosophy of the present work. Turner (1968) suggested an entrainment law based entirely on dimensional arguments which integrates the Peclet number Pe without test it experimentally:

$$\frac{u_e}{u'} \ \alpha \ Ri^{-3/2} Pe^{-1/2}$$

Following the work of E and Hopfinger (1986), Mory (1991) developed also an entrainment model taking into account the effect of molecular diffusivity with an assumption that mixing and entrainment was performed simultaneously by the same range of turbulent eddies. Nevertheless his work was essentially theoretical and comparison with particular experiments difficult.

Almost all the studies considered an infinitely thin interface. Breindenthal (1992) considered a thin interface with a thickness less than the kolmogorov microscale so that the interface cannot introduce another length scale into the entrainment problem. According to Fernando (1989), the entrainment occurs by the impinging eddies on the interfacial layer that scour and detach thin elements of fluid from it and mix them with the rest of the mixed layer.

However, when the density step $\Delta\rho$ between two stratified mixed layers is important, the kinetic energy contained in the fluid is insufficient to entrain fluid straight from the lower layer to the upper layer and vice versa(Ri is high). Then, entrainment can only occur on fluid which presents a weaker density variation with the mixed layer. This cannot exist only if we consider an interface with a known thickness and continuous density profile. This interface thickness is the result of a competition between thickening related to the mixing and the diffusion within the interface, and the thinning down of this interface by entrainment.

Therefore the model which we propose is a serial model contrary with other models that exists, with a step of diffusion in the interface and entrainment near its frontiers. The present dimensional development is based on three constant which were adjust by comparison with the previous experiments of Zellouf et al. (2005)

2 Industrial phenomenon

Industrial processes involving double-diffusion are numerous but the case of the LNG storage tank is quite unique with very large dimensions more than 50 meters. Then the flows behave as complex as geophysical flows.

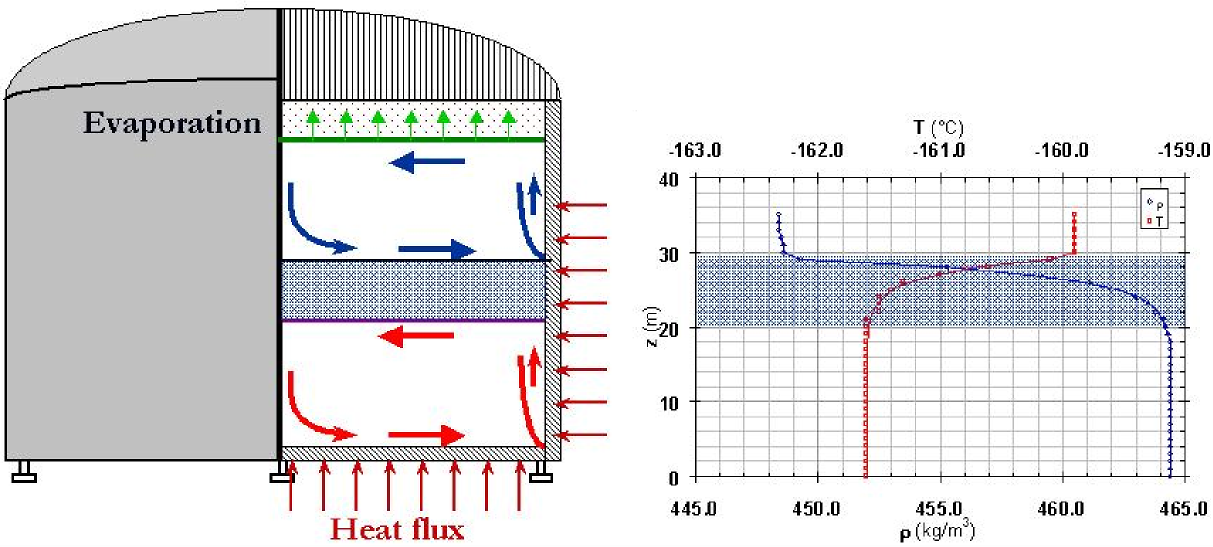


FIG. 1 – LNG storage tank with a stratified interface between two different LNG.

The figure 1 draws the case of a LNG tank filled with two LNG different in composition: the lighter LNG in the upper layer is able to release the parietal heating through the free surface by evaporation contrary to the heavier LNG in the lower layer where natural convection is blocked by the density gradient in the interface. The thickness of this interface was estimated around 10 meters and evolves with time. As the temperature of the lower layer increases the density difference decreases up to a condition of instabilities, which can either induce a progressive mixing with a global entrainment of the interface or can induce an abrupt incident called the “roll-over”.

3 Experiments

As the key point to foresee the mixing of the two previous LNG layers is the integration in time of the heat and mass flux across the interface submitted to a turbulent natural convection, we decided to extract the most simple situation: an interface stratified by only one property, either temperature or salt, submitted to a well-known grid generated turbulence in order to be in a forced convection 1D transfer case.

3.1 Experimental apparatus

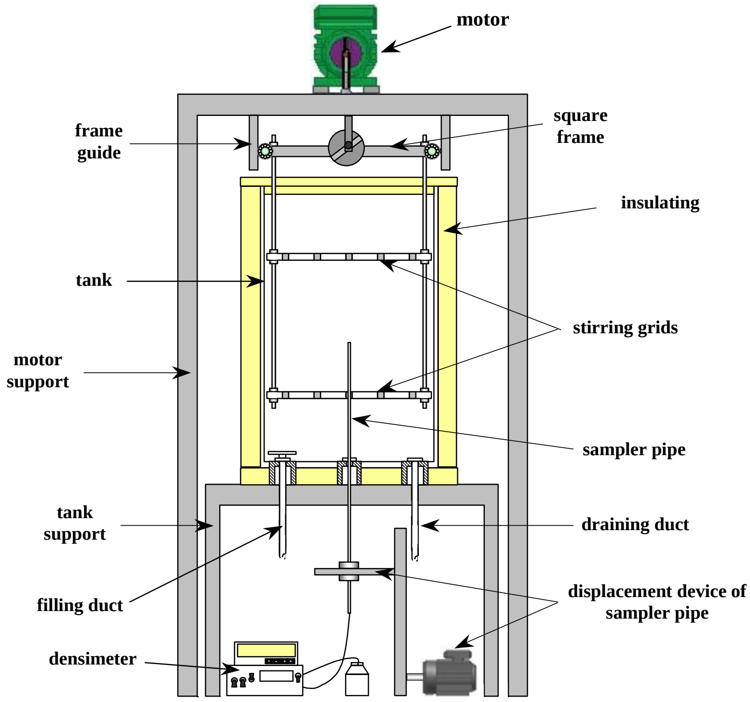


FIG. 1 – Experimental apparatus

The apparatus developed during the PhD work of Yacine Zellouf was previously reported in Zellouf et al. (2005). Vertical density profiles are performed by a travelling sampler pipe carrying fluid to a densimeter for the salt case and a thermocouple at the top of the same pipe for the thermal case. Salinity or density are then obtained through our calibrated formula:

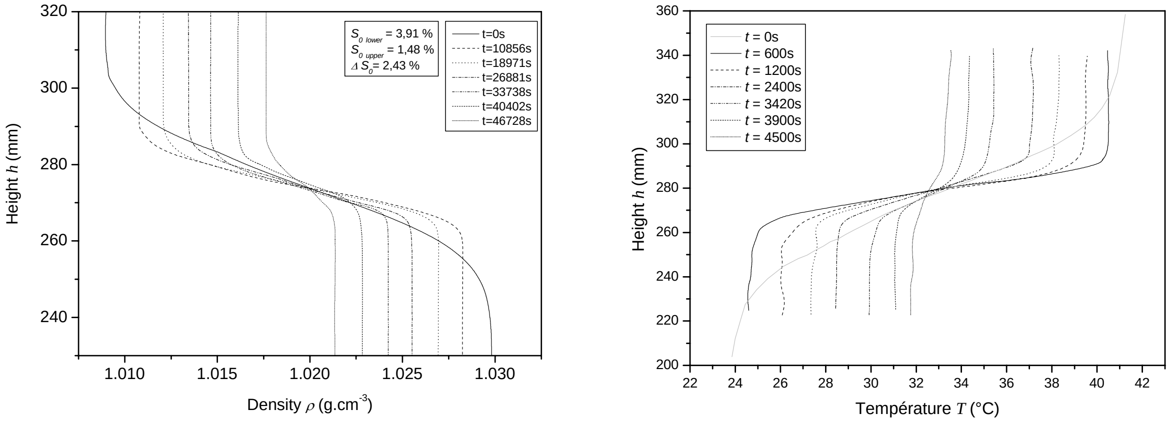
$$\rho(T,S) = \rho_0(T_0,S_0).\left[1-\alpha\left(T-T_0\right)+\beta\left(S-S_0\right)\right]$$

with T_0=20°C, S_0=0%, α=0,00031 °C^{-1} and β=0,0072%$^{-1}$.

As the transfer is managed by the turbulent flows above and below the interface we performed extensive PIV measurements in order to know exactly the length and velocity scales of the turbulent eddies at the position of the interface exactly in the middle of the tank. In the following the frequency and stroke of the grid oscillation was fixed and the corresponding turbulent scaling was given in the table 1.

3.2 Heat and mass flux measurements

The evolution of the density during the experiments is reported in the figure 2 and is quite identical for the two cases. The interface did not move vertically, its thickness was reduced until the gradient vanished. Note that the time duration of the salt stratified experiment is larger than for the temperature stratified one.



(a) (b)

FIG. 2 –Evolution of vertical density profile in time, (a) in salt stratified case and (b) in a temperature stratified case

From these profiles it is easy two extract the interfacial flux from a budget in the upper (sup) or lower (inf) layer:

For the heat flux:

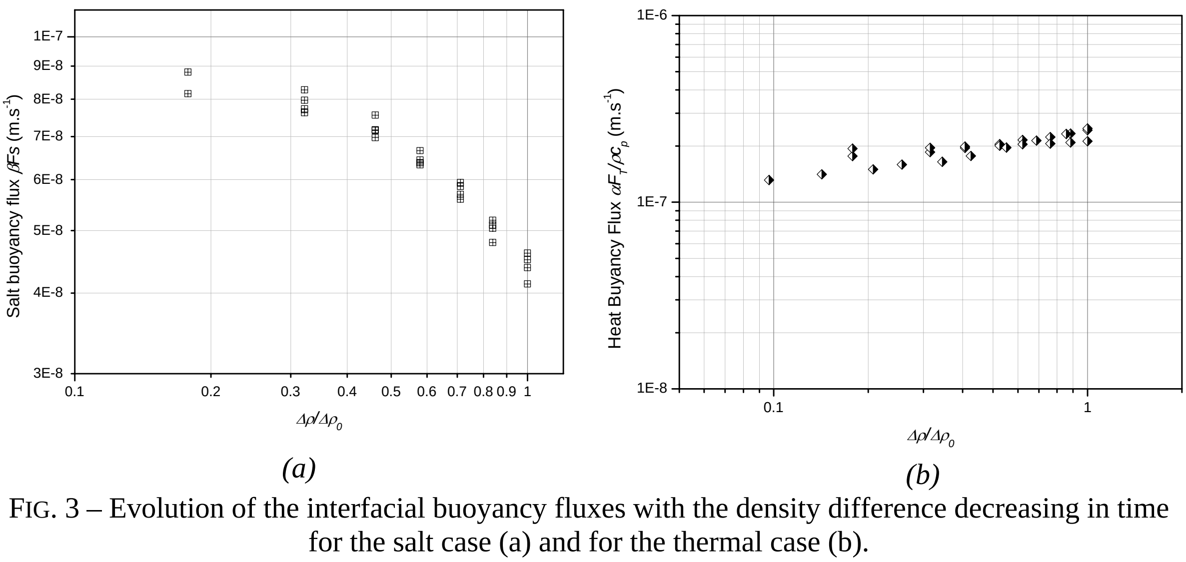
$$A_{int}\frac{d}{dt}\left(\rho_{inf}c_pT_{inf}h_{inf}\right)=F_tA_{int}-\left(\varphi_{pertes}A\right)_{inf}$$

$$-A_{int}\frac{d}{dt}\left(\rho_{sup}c_pT_{sup}h_{sup}\right)=F_tA_{int}+\left(\varphi_{pertes}A\right)_{sup}$$

For the salt flux:

$$F_s=-\frac{d}{dt}\left(\rho_{inf}h_{inf}S_{inf}\right)=\frac{d}{dt}\left(\rho_{sup}h_{sup}S_{sup}\right)$$

In order to compare the two fluxes we reduced them to the same dimension in term of buoyancy fluxes and plotted them against the relative density difference between the layers in figure 3. The most surprising result is the opposite behaviour with a negative power in the case



(a) *(b)*

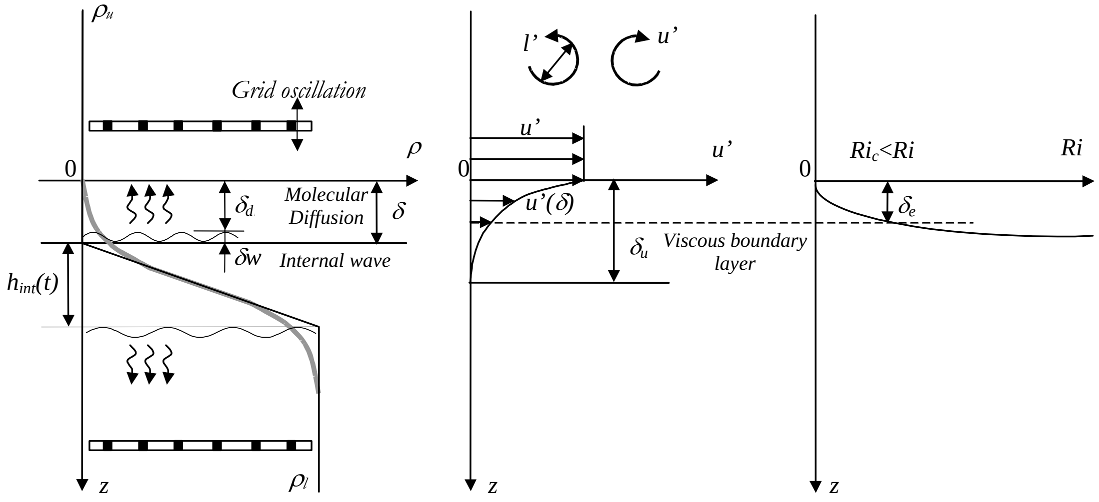
FIG. 3 – Evolution of the interfacial buoyancy fluxes with the density difference decreasing in time for the salt case (a) and for the thermal case (b).

of salt and positive in the case of temperature. For the same range of relative density difference the buoyancy flux is almost higher in the temperature-stratified case but the value of these fluxes evolve towards the same value for weak stratification.

As a matter of fact the density difference has opposite effect increasing diffusive transfer and decreasing vertical motion in the interface. It seems that the balance between the two is managed by the value of the molecular diffusion which is the only difference between the two cases.

3 Phenomenological model

Most of the models intending to follow the transfer across those interfaces distinguished two modes of transfer: diffusion in the thickness of the interface and direct fluid penetration through the interface (Linden 1974). This assumption was in contradiction to the large value of the global Richardson number $Ri = (sg\ \Delta\rho/\rho\ l')/u'$ which is always large except at the roll-over stage. Thus complete penetration of the interface by fluid of one layer is not possible. We decided to build an equivalent serial scheme where the transfer has always a diffusive step inside the interface (see figure 4) and entrainment (convective transfer) of fluid of the interface by the turbulent eddies. The opposite effect of the density gradient is then clearly identify with the diffusion inside the interface and the entrainment governed by a local Richardson number (figure 4 and Table 1). This model are then able to foresee the thickness of the interface which is increased by diffusion and is reduced by entrainment.



(a) (b) (c)

FIG. 4 –Schematic diagram of entrainment mechanism with three successive steps: (a) thickening of the interface through molecular diffusion and internal wave mixing, (b) diffusion of momentum and then (c) entrainment in the layer with a local Richardson number lower than a critical value.

In order to take into account the mixing phenomenon inside the interface, a mixing length δ_w due to the internal wave breaking completes the thickening of the interface by diffusion. This "turbulent diffusion" inside the interface is assumed to be proportional to the internal wave amplitude generated by the turbulent eddies inside the interface (table 1).

$l'=12mm$	$u'=2.5\ mm.s^{-1}$	$t=l'/u'$
$\delta_w = Ri_w \dfrac{u'^2}{g\,\Delta\rho/\rho_u}$	$\delta_d = C_1\sqrt{kt}$	$\delta = \delta_d + \delta_w$
$\delta_u = C_2\sqrt{\nu t}$	$Ri(z) = g\dfrac{\delta\rho(z)}{\rho_u}\dfrac{l'(z)}{u'(z)^2} << Ri = g\dfrac{\Delta\rho}{\rho_u}\dfrac{l'}{u'^2}$	$\delta_e = \dfrac{1}{4}\left(-1+\sqrt{1+8\dfrac{Ri_c}{Ri}\dfrac{h_{int}}{\delta_u}}\right)\delta_u$

TABLE 1 – values and definitions of the model parameters

In order to adapt all the assumptions to the reality of the experiments, the values of C_1, C_2, Ri_w and Ri_c should be optimised. There exists an infinite set of values that could fit the experiments and which should be analysed more systematically in the future. In this work we decided to take classic values of $C_1=1$, $Ri_w=0.25$ and the best fit of the model on both salt and temperature cases have given $C_1=2.7$ and $Ri_w=42$.

The comparison between the calculated transfer and the experiments is drawn on figure 5 in term of the entrainment rate versus the transient global Richardson number as Turner have done. The slopes in the loglog scaling exhibit the same power values as Turner found, -1.5 for the salt and –1 for the temperature case.

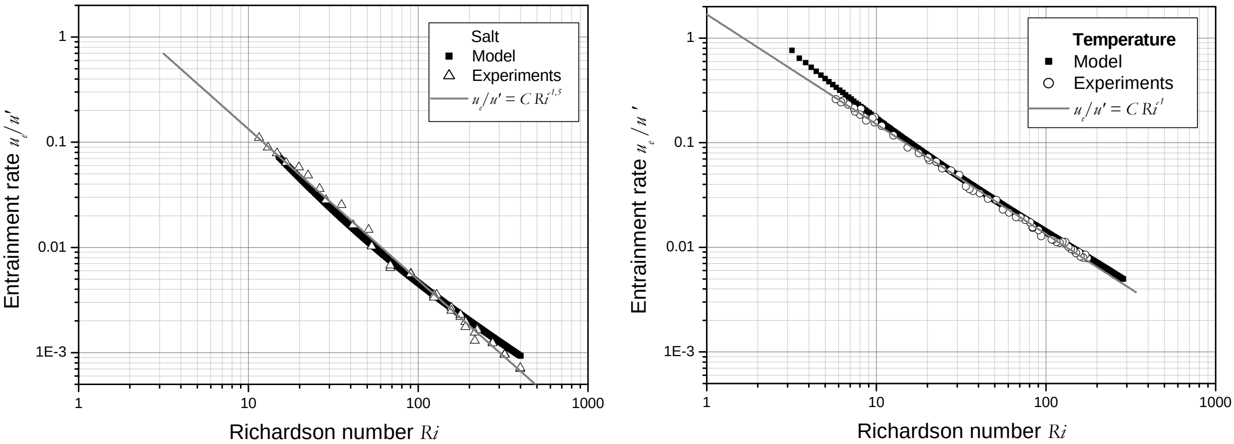


FIG. 1 – Entrainment rate comparison between experiment and model

4 Conclusions

This very simple model is able to reproduce the destruction of the stratification in the case of a density interface stirred by turbulence in a single diffusive case with two extreme dimensionless diffusivity k/ν=4 and 800. It is especially able to reproduce the two opposite effects of the property step ΔX on the ΔX flux: ΔX increases the diffusive flux across the interface but it inhibits the entrainment flux. Now the understanding of the molecular diffusivity effect is quite clear and future consideration of double or multi-diffusive interfaces will be easy.

An other quite simple development should be to predict these entrainment for numerous different Peclet number in order to compare the entrainment rates at the same Richardson number and then to obtain a continuous correlation in the (*Ri*,*Pe*) space as Turner (1968) and Mory (1991) have proposed.

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