TOWARDS A MULTI-SCALE APPROACH OF TWO-PHASE FLOW MODELING IN THE CONTEXT OF DNB MODELING

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Abstract

In this paper, we present how DNS is being used in the context of DNB modeling. Two particular applications are presented: wall boiling and bubble column flow. An analysis of the relevant length scales involved shows that true DNS, where all the length scales are resolved, is necessarily restricted to flow configurations where one or a few bubbles are involved. In the context of DNB modeling, DNS can thus be used to study (i) the dynamics of the growth of a few bubbles with their eventual spreading and (ii) bubble column flows to predict the void fraction field in the near wall region. To account for collective effects in bubbly flows, we show that it is necessary to develop a new approach where the large turbulence structures and large interface deformations are captured whereas the smallest scales are modeled; this is the ISS method. The DNS and ISS methods are presented and preliminary results on the use of DNS for larger scales models are presented.

1 Introduction

Studies related to nuclear reactor safety currently rely on system computer codes. These codes are based on two-phase averaged models, such as the two-fluid model, that need to be closed. The closure relations have been developed and extensively validated thanks to many experimental results. In system computer codes, the models are mainly one-dimensional and the typical length scales captured are rather large since they are of the order of a few decimeters. However, physical phenomena at this large scale may depend on smaller scale phenomena that the model cannot and is not intended to capture: they must be modeled. For particularly complex phenomena, this modeling is difficult, associated uncertainties are rather large and safety margins are thus necessary. This is why the current trend is to use smaller scale models and related codes in order to get more local and thus more accurate results. This general road map is already applied for single-phase flow modeling and industries, such as the aeronautic industry, routinely use, for some specific applications, models that are more accurate than the classical Reynolds Averaged Navier-Stokes (RANS) models, such as Large Eddy Simulation. Even though two-phase flow modeling is more complex, Computational Fluid Dynamics (CFD) is the natural trend in two-phase flow modeling as well; one talks about Computational Multifluid Flow Dynamics (CMFD).

1.1 Two-phase flow modeling

The models used in CMFD are the equivalent of the 3D RANS models in single-phase CFD. They are thus *averaged models* that require specific closure models. The physical origin of the closure models is twofold: (i) *turbulence* and (ii) *interfacial* transfers. Single-phase turbulence models have been extensively developed and can be considered as well-known (even though progress is still necessary). Two-phase turbulent flows are much more complex to model because of interfacial transfers that are of crucial importance in mass, momentum and energy transfers (the latter being of primary importance in nuclear reactor safety). Moreover, interfacial and turbulence transfers are coupled in a rather complex way because, in general, (i) it is not possible to apply a scale separation between the structures of turbulence and the size of the interfaces (as for particle flows for instance) and (ii) basic transfer mechanisms are unknown (no equivalence of the Kolmogorov turbulence energy cascade in single-phase flows exists in two-phase flows). Because of these theoretical difficulties, closure relations must resort on simplifying assumptions, such as the bubble shape in bubbly flows for instance. These simplifying assumptions, as well as a lack of knowledge regarding the fundamental nature of interface-turbulence transfers, limit the range of validity of the corresponding closure models. Nevertheless, despite the modeling difficulties associated to averaged models, it must be acknowledged that they are the only models that can be applied to study industrial flows.

1.2 DNS of two-phase flows

In single-phase flows, Direct Numerical Simulation (DNS) consists in capturing *all* the turbulence scales of the flow, from the largest integral scale down to the smallest Kolmogorov scale. In two-phase flows, DNS consists in capturing not only all the scales of the liquid and gas phases but also to capture *all the individual interfaces* of the flow, as illustrated in Fig. 1(a). From a technical point of view, DNS of two-phase flows is much more complex than DNS of single-phase flows, the main extra difficulty coming from the numerical treatment of the interfaces. Indeed, it is necessary to capture the discontinuities associated to the interfaces (e.g., mass density, heat flux, etc.) precisely and efficiently. Nevertheless, after about two decades of development, DNS methods are now getting mature enough to be used in applications of interest, as shown in the remainder of this paper.

DNS is potentially very powerful because it allows to get access to very detailed information in time and space. For instance, information such as the velocity-temperature correlations $\langle u'T' \rangle$ are very difficult to determine experimentally, in particular in high pressure and temperature conditions characteristic of nuclear safety issues, whereas this information is easily accessible numerically. However, getting this information requires a very large computational cost. Indeed, capturing all the turbulence scales of the flow requires a number of mesh points proportional to $Re^{9/4}$, where Re is the Reynolds number. Therefore, the range of application of DNS is and will always be limited (today to $Re < 10^5$ at most in single-phase flows), even though the continuous increase of available computational power will continuously broaden its range of application.

1.3 General road map

In the general perspective of two-phase flow modeling, the purpose of DNS is to go beyond the current limitations of two-phase flow models by (i) studying basic physical mechanisms, (ii) getting detailed information not accessible through experiments and (iii) assessing, improving or determining averaged closure relations. However, because of the large computational cost required, it is necessary to define the necessarily simple cases where DNS can be relevantly used. Many configurations deserve to be studied by DNS, but it is impossible to treat them all. Moreover, our current limited knowledge of turbulent two-phase flows prevents the use of a comprehensive matrix of basic flow configurations that would cover all the flow configurations encountered in a general two-phase flow. This is why the following three-step road map has been developed to define the basic flow configurations that should be studied by DNS.

1. The main industrial issues related to nuclear reactor safety are identified.
2. For each industrial issue, the key physical phenomena that are of crucial importance and that deserve improvements are identified.
3. Simple basic configurations are defined such that (i) the key physical phenomena are present and (ii) they can be treated with DNS (not too large computations).

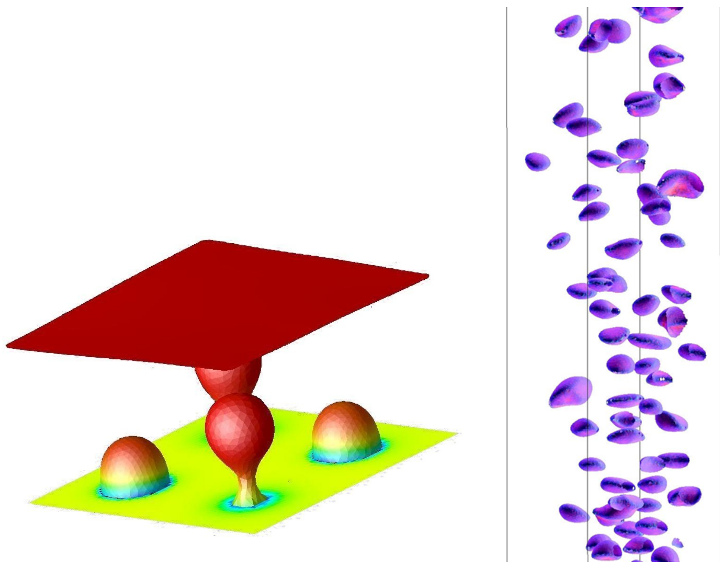
In the following, this road map is briefly presented for the case of Departure from Nucleate Boiling (DNB).

2 DNB modeling: a necessary multi-scale approach

Because of its potential destructive effect, DNB has long been identified as the most important issue related to nuclear reactor safety: preventing the occurrence of DNB is a major safety requirement.

The general goal is to determine a predictive model for the occurrence of DNB that can be used in CMFD models. This determination is particularly challenging for two main reasons. First, despite several decades of research, the basic physical mechanisms that trigger the occurrence of the boiling crisis are still unknown. It is thus very difficult to model this phenomenon that cannot be described… Second, DNB is characterized by a sudden increase of the void fraction at the wall. This sudden increase is likely to be influenced by the void fraction field in the vicinity of the wall just before the occurrence of DNB. It turns out that, even for isothermal flows without phase-change, capturing the correct void fraction field in a duct is difficult. This is because the void fraction field is highly influenced by the forces acting on the bubbles and more precisely by the competition of the lift and turbulent dispersion forces.

This analysis shows that the key physical mechanisms involved in the modeling of DNB occur at the scale of a few bubbles, either in wall boiling or in bubble flows. In both cases, DNS can be used to improve our knowledge on basic physical phenomena involved as well as our modeling capabilities.



(a) Wall boiling (b) Bubble column flow

Fig. 1: Examples of basic configurations related to DNB where DNS is relevant.

2.1 Wall boiling

Recent experimental results [e.g., Theofanous et al., 2002, Nishio and Tanaka, 2004] show that the triggering mechanism of the boiling crisis is very likely to occur very close to the wall, i.e., at the scale a few bubbles where very small length and time scales are involved. This explains why past attempts to model boiling crisis based on large scale mechanisms, such as the famous Zuber model, have failed to be used in CMFD codes to *predict* the occurrence of DNB. Thus, in order to study the basic physical mechanisms at the origin of DNB, it is necessary to study the development and eventual spreading of a few individual bubbles at a heated wall and DNS is therefore the relevant technique to be used (in complement with dedicated experiments).

However, even at this small scale, a multi-scale approach is necessary to get quantitative results. Indeed, in typical conditions, the bubble size at departure from the heated wall is thought to be of the order of 100 μm. Because DNS is meant to capture all individual bubbles, all the length scales up to this size must be captured. Considering a regular mesh, the current computational capacities are such that physical phenomena occurring at scales smaller than about 1 μm cannot be captured (unless Adaptive Mesh Refinement techniques are used). Any physical phenomenon occurring at scales smaller than 1 μm must thus be accounted for through specific subgrid scale models. Now, it turns out for wall boiling, a significant amount of the heat and mass transfer occur at length scales smaller than 1 μm. This means that, to get *quantitative* results, it is necessary to model phenomena ranging from about 0.01 μm to about

100 µm. It is thus necessary to develop and implement subgrid triple line models. However, it must be noted that *qualitative* results obtained without such subgrid models might provide interesting qualitative results.

2.2 Bubble column

Past experience in modeling and simulation of bubbly flows in pipes shows that the key phenomena that influence the void fraction distribution in the pipe and in particular in the vicinity of the wall where it is likely to influence the occurrence of DNB are the interfacial forces. More specifically, the important modeling phenomena to model accurately are the lift and turbulence dispersion forces acting on the bubbles. In order to determine the corresponding models, it is necessary to use simplifying assumptions on the bubble shape, on the creation of turbulent kinetic energy due to the bubbles and on the influence of the turbulence on the bubble motion. Because of a lack of detailed information on the flow turbulent characteristics, modeling such complex phenomena is challenging and the current approach has reached its limits. To go beyond these limitations, it is necessary to get access to this missing information. Since the relevant phenomena occur at the scale of a few interacting bubbles, DNS is very well suited to provide this detailed information. From the DNS results, the goal is to "measure" (numerically) the mean physical quantities of interest (such as the mean interfacial forces, mean turbulent kinetic energy, etc.) and to compare them to the correlations used to model them. This corresponds to *a priori* tests of the models. The next step in this upscaling approach will be to propose improvements of the current models that will be validated by DNS. However, as shown in the next section, even for simple bubbly flows involving several interacting bubbles, DNS is limited and an intermediate larger scale is necessary.

2.3 Need for an intermediate modeling scale: the ISS method

The relevant flow conditions that must be considered correspond to those existing in a sub-channel of a nuclear core. The typical size of a sub-channel is about 10^{-2} m, the typical bubble size is about 10^{-4} m, whereas the typical Kolmogorov scale is about 10^{-6} m. This analysis of orders of magnitude shows that about 10^{12} mesh points would be required for DNS to capture all the scales of the flow, which is *impossible* for current computing power. DNS must thus be limited to turbulent bubbly flows involving a very few bubbles. In order to study collective effects where many bubbles are involved, which is necessary to get relevant turbulent flow characteristics, the effect of the smallest scales of the flow must be accounted for through dedicated subgrid models. However, in order to keep the complex nature of the flow, each bubble should be described individually and the complex bubble deformations should be captured as well. Thus, the idea is to use standard single-phase Large Eddy Simulation (LES) models in the bulk phases by still capturing the large deformations of the interfaces; this is called the Interface and Subgrid Scale (ISS) method [Toutant, 2006]. This is illustrated in Fig. 2. As mentioned in the introduction, the main difficulties in two-phase flow modeling are related to interfacial transfers and this applies here since subgrid interface-turbulence transfers need to be modeled adequately.

2.4 Use of DNS and ISS results

Because of its complex nature, modeling DNB is a long-term perspective where DNS will play an important role in two aspects. First, it is currently developed to be used to study *fundamental physical mechanisms*. Two main mechanisms are studied: (i) the conditions under which the nucleate boiling gets suddenly unstable, which is characteristic of the boiling crisis, and (ii) interface-turbulence transfers with and without phase-change on individual or a few bubbles.

Second, as shown in the previous section, in turbulent conditions, collective effects cannot be studied by DNS because two many length scales are involved, which results in a prohibitive computational cost. This is why the ISS method is necessary to study collective effects. ISS requires the determination of subgrid terms that can be studied using DNS results (cf., section 3.2). ISS results will allow to make the link between local instantaneous models (i.e., where bubbles are described individually and where the interface deformations are accounted for) and averaged models where individual bubbles are not seen but

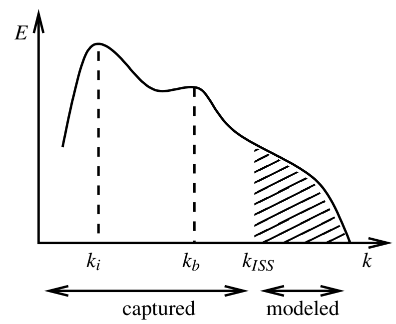


Fig. 2: Illustration of the Interfaces and Subgrid Scale (ISS) modeling on the turbulent kinetic energy spectrum (E is the kinetic turbulent energy and k is the wave number). The largest scales, including the integral scale (k_i) and the bubble scale (k_b) are captured by the model, whereas the smallest scales ($> k_{ISS}$) must be modeled using an adequate sub-grid model. It must be emphasized that such an energy spectrum and in particular the influence of the bubbles is only an illustrative representation and has not been firmly identified yet.

replaced by the void fraction. This second upscaling step is an open field of research that has just started to emerge thanks to the maturity of the DNS techniques and to the available computer power. For this second up-scaling step, different averaging operators are possible: statistical, volume or time averages. However, the time average is often used to derive the two-fluid model and to determine the corresponding closure relations. This multi-step upscaling approach is illustrated in Fig. 3.

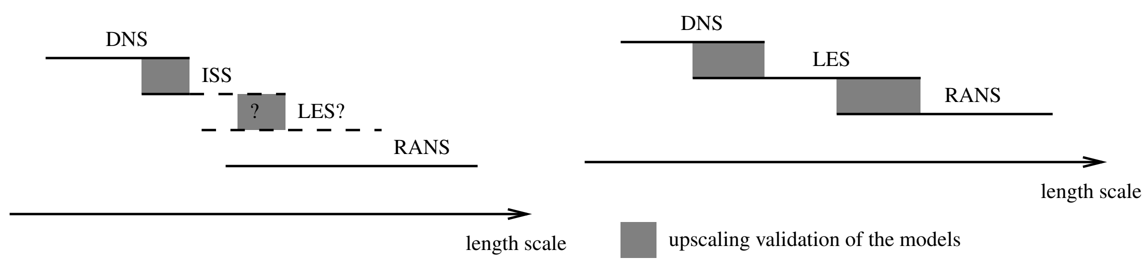


Fig. 3: Illustration of the range of application of the different models and of their up-scaling validation for two-phase and single-phase flows.

3 DNS and ISS methods and their validation

In this section, we present in more detail the DNS and ISS methods and their (specific) validation.

3.1 DNS method

The term “DNS” suggest that no model is required. However, for two-phase flows, models are required when the interface geometry is singular (during coalescence and fragmentation) and for strong heat and mass transfer (e.g., solid-liquid-gas triple line). These singularities deserve specific modeling, which is nevertheless beyond the purpose of this paper.

Several DNS methods exist, the most widely used being the Volume Of Fluid (VOF), Level Set and Front-Tracking methods [e.g., Lafaurie et al., 1994, Osher and Fedkiw, 2003, Tryggvason et al., 2001]. The current trend is to develop methods mixing the advantages of these three methods. This is the case of the method developed in our group [Mathieu, 2004], which is based on the Front-Tracking method: the equations of motion (mass, momentum and energy balance equations) are solved on a fixed

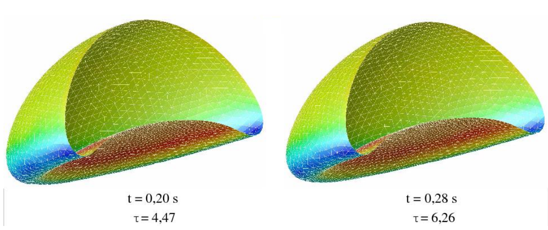
Eulerian mesh while the interface is represented by a Lagrangian mesh moving through the fixed Eulerian mesh. This is illustrated in Fig. 5(a) where the two-dimensional triangular mesh of a spherical bubble is represented. In any DNS method, two difficulties must be overcome: (i) interface tracking with minimum smearing of the interfacial discontinuities and (ii) accurate moving boundary conditions. In the Front-Tracking method, the first issue is eliminated *de facto* thanks to the use of a two-dimensional mesh for the interface. This positive effect is counter-balanced by the complex treatment of the interfacial mesh. Regarding the boundary conditions, the Ghost-Fluid Method (GFM) [Fedkiw et al., 1999] is extensively used. This method consists in getting more accurate derivatives at the interface by extending the field in the neighboring phase. It must be emphasized that, in most cases (i.e., apart from the triple line and during break-up and coalescence) the interfacial boundary conditions are known: they correspond to the well-established interfacial balance equations [e.g., Delhaye, 1974]. Thus the validation of a two-phase DNS focuses primarily on the accuracy of the treatment of the interfacial boundary conditions.

Our numerical method is continuously validated on a large series of dedicated test-cases [Lemonnier et al., 2005]. In this section, only two illustrative test-cases related to DNB are presented.

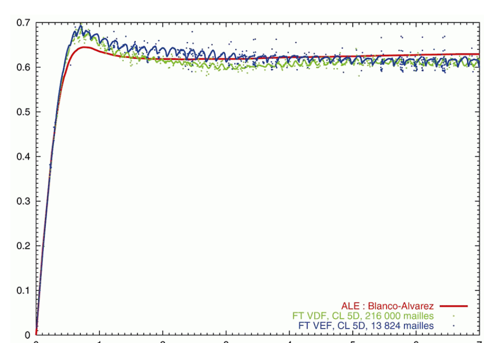
3.1.1 Rising bubble in a quiescent liquid

The main difficulty in the modeling of bubbly flows at the averaged scale in the determination and modeling of forces acting on bubbles that highly influence the void fraction field, in particular in the vicinity if the heated wall where it may influence the occurrence of DNB. This is why thoroughly validating the numerical method used on a single bubble is important. Indeed, the goal is to validate the method on known situations, determine the conditions under which good results are obtained and then use these criteria to study more complex situations for which no reference result exists and for which resorting to numerical simulations is thus interesting.

The test-case consists in simulating the rise of a gas bubble in a quiescent liquid. The flow is isothermal and no interfacial mass transfer exists. A reference numerical solution exist in [Blanco-Alvarez, 1995] where a very precise Arbitrary Lagrangian Eulerian (ALE) method has been used and the numerical results obtained with our Front-Tracking method are compared to this reference solution. This test-case assesses the combined and subtle effects of buoyancy, capillary, inertia and viscosity. The main parameter is the terminal velocity of the bubble V_b expressed in a non-dimensional form: $V_{adim} = V_b/(gD)$, where g is the acceleration of gravity and D is the bubble diameter. The simulation is fully three-dimensional and unsteady. For the non-dimensional parameters considered (i.e., $Eo = \rho_l g D^2/\sigma = 40$ and $Re = \rho_l U D/\mu_l = 20.6$, where ρ_l is the liquid density, σ is the surface tension and U is the bubble terminal velocity), the bubble reaches a constant rising velocity and its shape reaches a steady state (see Fig. 4).



(a) Shape of the rising bubble at steady state



(b) Time variation of the bubble rising velocity

Fig. 4: Result of the rising bubble test-case.

More quantitatively, the error on the terminal rising velocity is given in Tab. 1 for different discretizations. This table shows that the method converges and that, even for coarse meshes, the error is only about 1 %.

Tab. 1: Relative error of the bubble terminal velocity with the Front-Tracking method (N/D represents the number of mesh cells in the bubble diameter).

Method and discretization	N/D	V_{adim}	Error
ALE: Reference	–	0.630	–
FT: 32 000	4	0.638	1.3 %
FT: 108 000	6	0.637	1.1 %
FT: 256 000	8	0.624	1.0 %
FT: 864 000	12	0.627	0.5 %
FT: 1 492 992	14.4	0.629	0.1 %

This test-case allows to determine some best practice guidelines for the DNS of bubbly flows. In particular, it shows that about 15 mesh cells in the bubble diameter must be used in order to get accurate results.

3.1.2 Evaporation of a vapor bubble in a superheated liquid

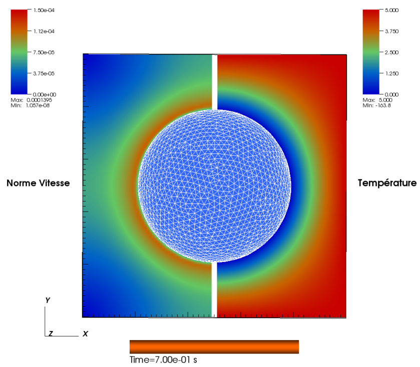
Flows involving phase-change are more complex to simulate because of the discontinuity of the fluid velocity at the interface. Thus, when phase-change occurs, the three velocities (interface, liquid and vapor) are all different at the interface and the determination of the speed of displacement of the interface is more difficult. Moreover, the problem is much more coupled than without phase-change. Thus, the two main issues are (i) the determination of the energy flux at the interface and the corresponding interfacial mass transfer and (ii) the determination of the speed of displacement of the interface. All these issues are non-trivial and the dedicated numerical techniques developed must be thoroughly validated.

In this perspective, we present the result of a three-dimensional test-case corresponding to the evaporation in zero-gravity of a vapor bubble in a quiescent superheated liquid. An analytical solution to this problem exists [Scriven, 1959] and the numerical results are compared to this analytical solution. The shape of the interface, the temperature field and the norm of the velocity field are presented in Fig. 5(a). This figure shows in particular that the thermal boundary layer is rather thin compared to the bubble diameter. Since the interfacial mass flow rate depends directly on the interfacial heat flux that is directly proportional to the interfacial temperature gradient, it shows that it is crucial to capture the thermal boundary layer to get good quantitative results. The quantitative comparison focuses on the time evolution of the bubble diameter $D(t)$: $D(t)^2$ must be a linear function of time. Fig. 5(b) shows that the numerical results are in good agreement with the theoretical solution. We showed that the numerical convergence on the slope of the function $D(t)^2$ is more than second order.

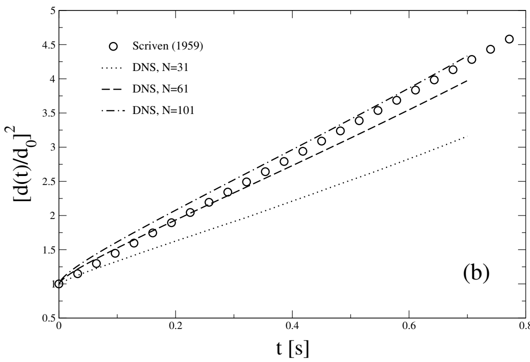
This test-case allows to determine some important best practice guidelines. In particular, it shows that, in order to get accurate results, it is necessary that the thermal boundary layer is captured by about 3-5 mesh points.

3.2 ISS method

As presented in section 2.3, DNS can be used to study very local phenomena on one or a few bubbles. To study collective effects while still resolving each bubble individually and the interface deformations, it is necessary to model the smallest scales of turbulence and of the interface deformations (see Fig. 2). The idea is to use classical single-phase LES within the bulk phases and to get a similar concept to model the subgrid interface deformations and subgrid interface-turbulence transfers. Because the LES concept is based on volume averaging, the idea is to apply the LES space filter not only within the bulk phases but also at the interface. Since the interface is filtered, the interface is transformed into a continuous transition zone as sketched in Fig. 6. We then get a continuous LES model. At this stage of the modeling, subgrid terms have to be closed. Such a continuous LES model is not well suited for numerical simulations because the interfacial transition zone should be captured by several mesh points,



(a) Snapshot of the temperature (right) and norm of the velocity (left) fields



(b) Comparison of the numerical results (lines) and the theoretical result (circles)

Fig. 5: DNS of the vaporization of a single vapor bubble in a super-heated liquid in zero-gravity conditions.

which would decrease the computational efficiency of the method: the idea is to use mesh cells whose size are that of the filter and not much smaller as would be required to capture the interfacial transition zone. It is then necessary to transform the continuous transition zone into an equivalent discontinuous (large) interface. The corresponding model is called the discontinuous LES model, or ISS model.

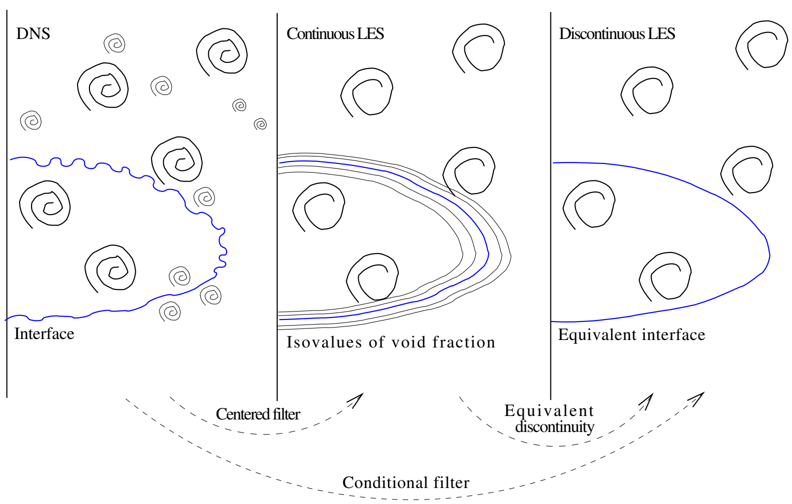


Fig. 6: The ISS modeling approach. Schematic representation of resolved coherent turbulence structures and interface in the case of a DNS, a continuous LES and a discontinuous LES.

Once this conceptual image is defined, it is necessary to develop the corresponding models. The purpose here is not to present the detailed theoretical developments but rather to present the model proposed and its validation (the interested reader can refer to [Toutant, 2006, Toutant et al., 2008c,a,b]). The variables corresponding to the discontinuous LES model are denoted $\tilde{\psi}$. The model proposed is the following:

$$\nabla \cdot \tilde{u} = 0 \tag{1}$$

$$\frac{\partial \tilde{\chi}}{\partial t} = \left(\tilde{u} \cdot \tilde{n} + \left(\overline{\tilde{u} \cdot \tilde{n}}^{\sigma} - \overline{\tilde{u}}^{\sigma} \cdot \overline{\tilde{n}}^{\sigma} \right) + \frac{r^2}{10} \left(\Delta_s \left(\frac{\partial \tilde{\chi}}{\partial t} \tilde{n} \right) \cdot \tilde{n} - 2 \nabla_s \left(\frac{\partial \tilde{\chi}}{\partial t} \tilde{n} \right) : \nabla_s \tilde{n} \right) \right) \delta_{\tilde{\sigma}} \tag{2}$$

$$\frac{\partial(\tilde{\rho}\,\tilde{u})}{\partial t} + \nabla\cdot(\tilde{\rho}\,\tilde{u}\otimes\tilde{u}) = -\nabla\tilde{p} + \nabla\cdot(\tilde{S} + \tilde{\rho}\,\tilde{\mathscr{L}}) - \left(\sigma\,\tilde{\kappa}\,\tilde{n} + \int_{-\infty}^{+\infty} \frac{\partial(\overline{\tilde{\rho}\,\tilde{u}} - \overline{\tilde{\rho}}\,\overline{\tilde{u}})}{\partial t}\, d\xi_3\right)\delta_{\tilde{\sigma}} \tag{3}$$

where $\tilde{u}$ is the fluid velocity, $\tilde{\chi}$ is the indicator function of the gas phase (which is discontinuous at the interface), $\tilde{n}$ is the unit normal to the ISS discontinuous interface $\overline{\psi}^{\sigma}$ represents the interfacial average of the quantity ψ, r represents the filter size, ξ_3 is the normal direction to the interface, ∇_s and Δ_s are the surface gradient and Laplacian operators, $\delta_{\tilde{\sigma}}$ is the Dirac delta function associated to the ISS discontinuous interface and

$$\tilde{\mathscr{L}} = \overline{\tilde{u}} \otimes \overline{\tilde{u}} - \overline{\tilde{u} \otimes \tilde{u}}$$

$$\tilde{S} = \mu\left(\nabla\tilde{u} + \nabla^T\tilde{u}\right)$$

where $\overline{\psi}$ represents the volume average of ψ (over the filter size r).

What is remarkable is Eq. (2) is that the speed of displacement of the interface is not simply the fluid velocity at the interface $\tilde{u}$ (as in DNS). If that were the case, only the first term of the right-hand-side of Eq. (2) would be present. Two other contributions are present. The first one is a scale-similarity term corresponding to the fluid-interface correlation and the second one is related to the time evolution of the surface curvature (coming from the fact that the interface has been filtered in space). This discontinuous ISS model and in particular these two terms appearing in the equation of evolution of the discontinuous filtered interface must be validated. This validation is performed on an academic and relevant simulation corresponding to the interaction of a rising bubble with an isotropic homogeneous turbulence as sketched in Fig. 7.

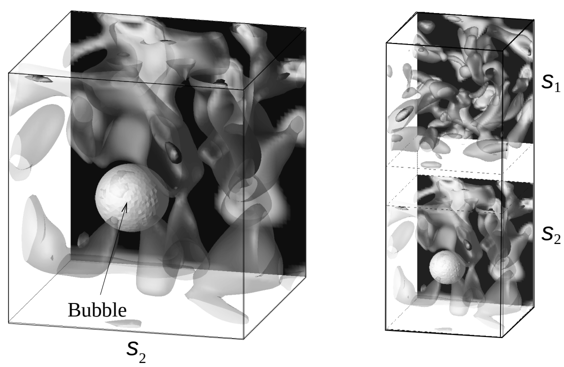


Fig. 7: Interaction of a rising bubble with an isotropic homogeneous turbulence. Simulation S_1 corresponds to the simulation of an isotropic homogeneous turbulence that is coupled with the simulation S_2 where the bubble is present. The bubble as well as isocontours of the Q-criterion (characteristic of the turbulence) are represented.

Using this DNS, it is possible to measure all the terms appearing in Eq. (2) and then to determine the relative importance of each one. The corresponding results are shown in Fig. 8 where the error on the interface transport is plotted when one of the two modeling terms appearing in Eq. (2) are accounted for and when both modeling terms are accounted for. This figure clearly shows that both terms are necessary to get a good approximation of the interface transport.

It is worth noting that this study corresponds to an example where DNS is used as a reference solution to determine and validate larger scale models (here, the ISS model).

4 Preliminary results

In this section, we present preliminary results about ongoing developments concerning the general multi-scale approach presented in section 2.

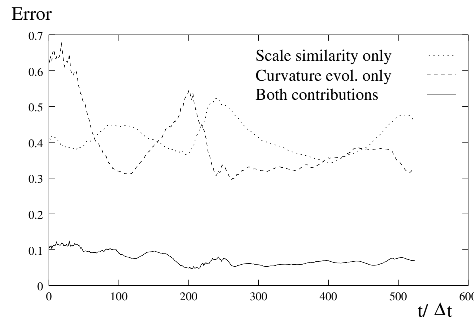
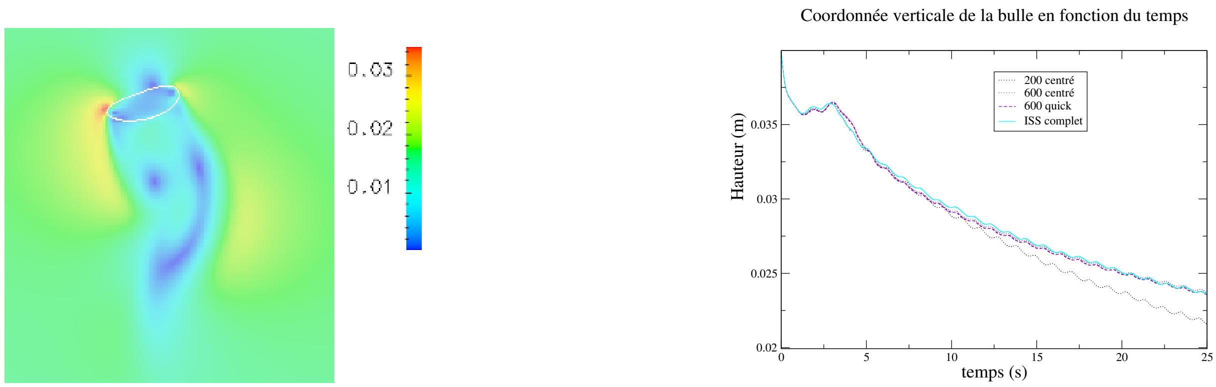


Fig. 8: Time evolution of the interface transport error in the case of a model (i) with only the similarity scale (dotted line), (ii) with only the time evolution of the curvature (dashed line) and (iii) combining the two terms (continuous line). The error is the difference between the actual speed of displacement of the ISS interface determined from DNS and the ISS model proposed.

The first case corresponds to the first *a posteriori* test of the ISS model. As presented in the previous section, the ISS model has been validated thanks to *a priori* tests based on DNS results *only*. Here, the ISS model (corresponding to Eqs. (1)-(3)) has been implemented (still using the Front-Tracking method described in section 3.1) and the results obtained with the ISS method are compared to those obtained with DNS. The goal is to check that similar results are obtained by DNS and ISS but with a coarser discretization with the ISS method: the subgrid ISS terms are supposed to account for important subgrid effects that cannot be captured by the discretization used and that must thus be accounted for through subgrid additional terms in the equations of motion (see section 3.2).

The test-case considered corresponds to a two-dimensional rising gas bubble in a quiescent liquid. The non-dimensional parameters considered ($Mo = g\,\mu_l^4/(\rho_l\,\sigma^3) \simeq 10^{-5}$ and $Eo \simeq 5$) are such that the rising bubble is wobbling as shown in Fig. 9(a). The validation is performed on the time evolution of the vertical component of the bubble velocity as shown in Fig. 9(b). The first simulation corresponds to an under-resolved DNS simulation on a coarse mesh (200 mesh cells). The second group of simulations corresponds to resolved DNS on a fine mesh (600 mesh points); these simulations are converged and can be considered as reference solutions. The last simulation corresponds to an ISS simulation on the coarse mesh (i.e., 200 mesh points). Fig. 9(b) shows that the ISS results obtained on the coarse are in very good agreement with the DNS results obtained on the fine mesh. This result shows that the ISS subgrid terms do account for the correct interface-turbulence transfers necessary to get the correct complex motion of the bubble. This result clearly indicates that the ISS method can confidently be used to predict the correct motion of bubbles and thus broadens the range of application of interface tracking methods to study many deformable bubble flows. This is an ongoing research, especially in three dimensions.

Because of the difficulties inherent to the DNS with phase-change, the strategy developed is first to study non-miscible and isothermal phenomena and then to extend the working methodology to phase-change phenomena. Because the ISS method has convincingly shown its potential to study larger scale phenomena, we currently develop the same strategy accounting for phase-change. As in the non-miscible case, the first step is to determine the terms that must be modeled and then to test the proposed closure relations thanks to *a priori* tests on resolved DNS. This is an ongoing work. One of the simulations considered is that of a two-dimensional bubble in a “turbulent” channel flow as shown in Fig. 10. In this study, the temperature of the channel walls is kept constant below the saturation temperature so that the bubble condenses. In two-phase averaged model, one of the key physical quantities is the volumetric mean interfacial area A_i. The time evolution of A_i is shown in Fig. 10(b). The variation of A_i is due to two phenomena: phase-change and turbulence-interface interactions. To determine the variations due to phase-change only, we use the bubble volume to determine the area of the equivalent circle (i.e., $2\sqrt{\pi V}$, where V is the –two-dimensional– bubble volume). Both surface area variations are plotted in Fig. 10(b). It is thus possible to determine the relative surface area due to turbulence as shown in Fig. 10(c). This figure shows that, in this particular case, the variation of the surface area can be up to



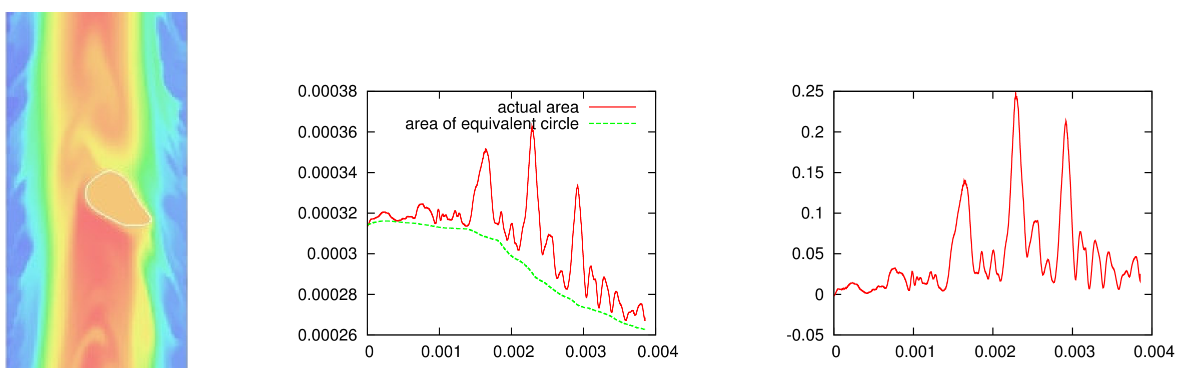
(a) Interface and norm of the velocity field during the bubble rise

(b) Time variation of the vertical position of the bubble for different DNS and with the ISS model

Fig. 9: *A posteriori* test of the ISS model on a two-dimensional case of a single rising bubble.

25% of the equilibrium circle surface area.

Even though these results are preliminary, they show how DNS can provide qualitative as well as quantitative results about complex interface-turbulence interactions that can be directly used to assess or develop averaged two-phase flow models.



(a) Shape of the interface and temperature field.

(b) Time variation of the actual bubble surface area and of the equivalent circular surface area (based on the bubble volume).

(c) Time variation of the relative surface area variation due to interface-turbulence interactions.

Fig. 10: Vapor bubble condensing in a two-dimensional “turbulent” channel flow and corresponding variations of the bubble surface area.

5 Conclusions and perspectives

In this paper, we present a multi-scale approach of two-phase flow modeling in the perspective of determination of predictive models for DNB. In the approach presented, DNS plays a central role and is applied to two particular relevant situations: wall boiling and bubble column flow. DNS is necessarily restricted to very small domains but can be applied to study basic physical mechanisms at the scale of one or a few bubbles. It is thus particularly relevant to study the triggering mechanism of the boiling crisis that involves very small time and length scales that are very difficult to capture experimentally. We also showed that, in a multi-scale approach of bubbly flows, multi-bubble collective effects cannot be studied by DNS and that larger scale models are necessary. This is why the ISS is being developed in order to capture the large scale turbulence structures and interface deformations and to account for the smallest scales effects through dedicated subgrid models. We showed that DNS is used to validate subgrid models. Preliminary results show the potential of DNS and ISS to assess averaged models of two-phase flows.

In future works, we will use DNS and ISS simulations to assess averaged models quantitatively. We will also develop ISS subgrid models for two-phase flows with phase-change.

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