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Assessment of grid adaptation criteria for steady, two-dimensional, inviscid flows in non-ideal compressible fluids

B. Re[a,*], C. Dobrzynski[b,c], A. Guardone[a]

[a] Department of Aerospace Science and Technology, Politecnico di Milano, Milano 20156, Italy
[b] Bordeaux INP, IMB, UMR 5251, F-33400, Talence, France
[c] Inria-Bordeaux Sud-Ouest, Team CARDAMOM, F-33405, Talence, France

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ABSTRACT

Two-dimensional simulations are carried out to assess standard grid adaptation criteria, widely used for ideal flows, for steady inviscid flows in the proximity of the liquid-vapor saturation curve, where non-ideal compressible-fluid behavior is expected. A van der Waals fluid description of the thermodynamic properties is assumed to account for non-ideal effects at least qualitatively. Nitrogen under-expanded nozzle jets are chosen as the reference flow to assess different adaptation criteria. Isotropic and anisotropic error estimators based on the derivatives of flow variables prove to be suitable to capture the rarefaction, the reflected shock and the constant-pressure jet boundary. Both density and Mach-based estimators are found to be very suitable to drive grid adaptation in the non-ideal compressible-fluid regime, which is characterized by large fluid compressibility. Then, similar adaptation criteria are used to simulate under-expanded nozzle jets of the siloxane MDM, a high molecular complexity fluid for which the van der Waals model predicts the existence of a thermodynamic region where the fundamental derivative of gasdynamics has values less than one. In this region, Mach number estimators prove to be more effective because of the non-ideal dependence of the speed of sound on the density and the temperature.

1. Introduction

Mesh adaptation proved to be a valuable tool for numerical simulations of fluid flows [1], with particular reference to fluid flows characterized by different spatial scales and to all situations where the general location of relevant flow features is not known a priori [2–4]. As it is well known, adaptation techniques aim at modifying the computational mesh to maximize its efficiency with respect to a given goal, therefore the definition of the criterion used to modify grid spacing is a key point in mesh adaptation and several approaches have been proposed. For example, integral error indicators obtained from the solution of the adjoint flow problem can be used to redistribute the mesh nodes to minimize the error in the evaluation of the output of interest, such as the aerodynamic force acting on a given solid body [5–7]. However, if not already available for some other purposes, the solution of the adjoint problem may be expensive [8]. Alternatively, a suitable local

* Corresponding author. Tel.: +393487540530.
E-mail addresses: barbara.re@polimi.it, barbarare88@gmail.com (B. Re).

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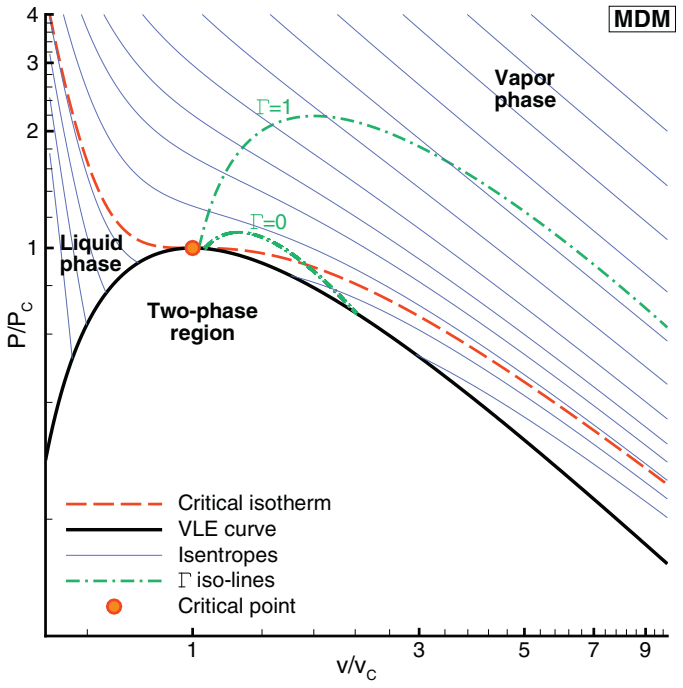

Fig. 1. Representative isentropes and liquid-vapor saturation curve in the $v-P$ plane in the non-ideal compressible-fluid region for the siloxane MDM under the polytropic van der Waals gas. The critical isotherm, the critical point and iso-lines of the fundamental derivative of gasdynamics Γ [21] are also shown.

error indicator can be built and the grid can be modified to equi-distribute the numerical error within the computational domain, i.e. the local mesh size can be increased (decreased) in regions where the error is estimated to be below (above) its average value [9–11]. For finite element discretizations, this estimates can be based on the interpolation error [12–15]. In fluid-dynamic problems, local mesh adaptation indicators are often functions of relevant flow variables, such as the density, the pressure, the Mach number or the velocity and on their first- and second-order derivatives. The underlying assumption of this approach is that the largest error occurs in the regions of the domain where the solution changes most rapidly, therefore the grid spacing is reduced where the gradients are large, while it is increased where the solution is smooth. Thanks to their simplicity and fast computation, this kind of adaptation criteria is widely and successfully used in various fluid-dynamics problems [16–18].

The main drawback of the adaptive indicators based on flow variables is that the optimal indicator for the problem under investigation, i.e. the variable (or combination of variables) that allows to efficiently detect the relevant flow structures, is usually problem-dependent. However, some general assumptions can be stated on the based of the expected flow behavior, as for instance the presence of shock waves, vortex structures or rarefaction fan. In this regards, since the relationships among the diverse flow variables strongly depend on the assumed thermodynamic model, the selection of the proper error indicator is not straightforward if the fluid thermodynamics departs from the well-known ideal-gas conditions, for which a wealth of literature regarding the effectiveness of the error indicators is already available [2,3,19]. The above is indeed the case for the so-called non-ideal compressible-fluid dynamics (NICFD), the branch of fluid dynamics devoted to the study of compressible fluids in the vicinity of the liquid-vapor saturation curve and critical point, see Fig. 1. In NICFD, non-ideal thermodynamics results in large compressibility of the fluid, non-ideal dependence of the speed of sound on the density, critical point phenomena, phase transition. For fluids characterized by large molecular complexity, non-classical gasdynamics behavior is possibly observed [20]. Therefore, the applicability of mesh adaptation criteria derived for the constant-specific-heat ideal-gas case is questionable in these highly non-ideal flow conditions.

The present work is a first, tentative assessment of local mesh adaptation criteria for steady two-dimensional NICFD under the inviscid assumption. To this purpose, numerical simulations of supersonic under-expanded nozzle jets of nitrogen and siloxane MDM[1], operating close to the liquid-vapor saturation curve are performed to study the effectiveness of different adaptation criteria. These include combinations of the gradient and the Hessian of the pressure, the Mach number, the density and the temperature, within a multi-passage adaptation strategy that allows to detect weaker phenomena [22]. Moreover, given the nature of the flow, also anisotropic mesh adaptation is exploited [10,23]. The van der Waals

[1] MDM is the acronym for the octamethyltrisiloxane according to the standard nomenclature for siloxanes based on building blocks, which in this case are the M- and D-units. The chemical formula of MDM is $C_8H_{24}Si_3O_2$.

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