Ghost vortices and disappearing bodies: the concept of momentum and impulse

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Phase change occurs in many common dispersed multiphase flows, such as during nucleate boiling of subcooled liquids (eg water in a kettle), by evaporating fuel sprays (eg inside the combustion chamber of a gasoline engine) and melting of ice particles in water. A common factor in these problems is that discrete bodies move and disappear. In the case of condensing vapour bubbles created during boiling, the majority of the momentum is carried by the fluid. When volatile fuel is sprayed into a gas, the droplets which form initially carry the entire momentum of the system. The consequence of these discrete bodies moving and disappearing in an unbounded flow is profound - a `ghost' vortex is left behind after these bodies have disappeared. In many examples the vortex is sufficiently compact that it can be observed – an example is given below.

A whole range of diagnostic tools have been developed and applied to study turbulence and vortical flows, for instance integral constraints such as helicity, (angular/linear) impulse, circulation and kinetic energy (see Hunt, Delfos, Eames & Perkins 2007) have been used to provide general insight into these flows. But in the field of dispersed multiphase flows, integral constraints have only been applied in a few instance to study the flow past bodies impulsively set into motion (Felderhof 2007), or interacting with vortices. Perhaps the most well-known integral relationship in two-phase flows is Betz's (1925) relationship between the drag on a body and its volume flux deficit downstream. Momentum is potentially the most useful integral quantity for fluid mechanics. Perhaps one reason that it has not been used for unbounded flows is that its heuristic definition, as the integral of density weighted velocity over a flow domain, is ill-defined since the velocity decays so slowly in the far field that the integral depends of the shape of the domain at infinity (Theodorsen 1941). This deficiency is described in few textbooks on fluid mechanics and is not broadly recognised. This is perhaps why the fluid mechanics community have tended to use the concept of impulse, a concept which is only useful for fluids with a homogeneous density field (Saffman 1972).

Dispersed flows with phase change certainly represents one of the most challenging areas of multiphase flows because the chemical and thermal processes which accompany them are complex. One unexplored avenue is to consider the global momentum balance. The complex thermal and chemical processes associated with phase change are clearly important in setting the disappearance time scale of the bodies and kinetic energy in the external flow, but in some cases they do not affect the momentum flux into the ambient fluid. In developing a general framework to study momentum globally and resolve the issue of how to define momentum unambiguously. We shall show that this expression is equivalent to Lighthill's (1986) formulation (for fluids of uniform density), but the effect of an inhomogeneous density field (which may be important during droplet evaporation) introduces additional new terms. We bring together in one formulation, the generation of a ghost vortex by a vapour bubble collapsing and a droplet evaporation. For the case of nucleate boiling, we report new experimental observations of a ghost vortex signature being generated by the disappearance of single bubbles. The degree of subcooling is sufficiently high that in many cases the bubbles go through a topological change, but in general the vortex is generated by a viscous mechanism. While the observations are consistent with our physical model, the contribution to the momentum of the vortex from the bubble growing and rising is not included in our estimates. For evaporating droplets, we have shown that Betz' (1925) relationship between drag and wake volume flux no longer holds. The evaporative flux separates the wake inhibiting vorticity cancellation and causing the wake velocity deficit to decay (in the near field) more slowly than for a rigid body.

The examples in this paper aim to demonstrate that integral invariants are a powerful tool, providing a new perspective to understanding the global behaviour of dispersed multiphase flows.

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