Computational Cloud Dynamics

By Liz Marshall, Fluent Inc.

Clouds are blankets for the earth. They trap moisture that evaporates from the surface, store it, and return it to the earth in the form of rain, snow, sleet, and hail. Clouds form when moist air is forced upward into the atmosphere. As the air cools, the vapor condenses onto natural and man-made aerosol particles, forming tiny droplets. The shape of the cloud that develops is a function of local wind and temperature gradients. The droplets and air in and around clouds constitute a multiphase system. While large-scale computational weather modeling is still the domain of national weather services, an attempt to simulate a simple – yet rare – cloud formation has recently been carried out using FLUENT.

The cloud formation of interest is named for the Kelvin-Helmholtz instability, which is well known to scientists, since it appears in so many forms in nature and laboratory applications. It occurs at the interface of two fluids, usually of different density in a gravitational field, when their streamwise velocities differ. Transverse velocity gradients develop in both fluids, and these serve as a source of free energy that feeds perturbations at the interface, causing them to grow. In addition to cloud shapes in the sky, the Kelvin-Helmholtz instability can be observed in sand dunes, rising cigarette smoke, and water waves.

Using the mixture multiphase model in FLUENT, a simplified Kelvin-Helmholtz cloud formation was simulated. A 2D rectangular domain 2.5 km long and 2 km high was modeled using a quad mesh of 50,000 cells. At the start of the transient simulation, air filled the upper half of the domain, and cloud material, consisting of 1 micron water droplets, filled the lower half. The densities of air and clouds are difficult to estimate. Indeed, clouds are dynamic entities, with varying properties that result from ongoing heat, mass, and momentum transfer. As the height above the earth increases, the density of air decreases. Clouds of different types form at different heights; each is therefore less dense on average than the air below it, and more dense on average than the air above it. Since Kelvin-Helmholtz cloud formations are normally observed on the upper, rather than the lower boundary of a cloud, a case was considered with the cloud density greater than that of air. A 10% difference in density and a 10 km/hr difference in velocity across the cloud/air interface were assumed.

The interface was perturbed in a sinusoidal pattern using five wave cycles. A published nonlinear calculation of a Kelvin-Helmholtz instability using two fluids of equal density indicates that a wave of this scale should break between 63 and 72 seconds if the surface is initially perturbed [1, 2]. The FLUENT results using a 10% density difference were found to break at about 80 seconds. As the calculation continued beyond this point, the waves continued to curl, and eventually broke altogether. Other cases studied made use of smaller or larger velocity differences or three, rather than five full cycles of initial perturbation. Each case followed the same general pattern, requiring a somewhat longer time to reach the break point when compared to the equal density calculations reported in the literature. ■

references:

1 Pijush K. Kundu, Fluid Mechanics, San Diego, Academic Press, Inc. 1990.

2 J.S. Turner, Buoyancy Effects in Fluids, London, Cambridge University Press, 1973.

Breaking Kelvin-Helmholtz waves in clouds over Laramie, Wyoming, USA

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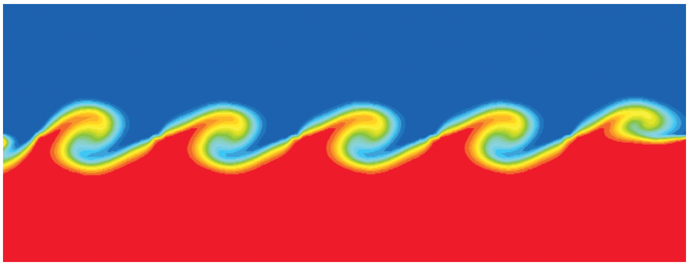
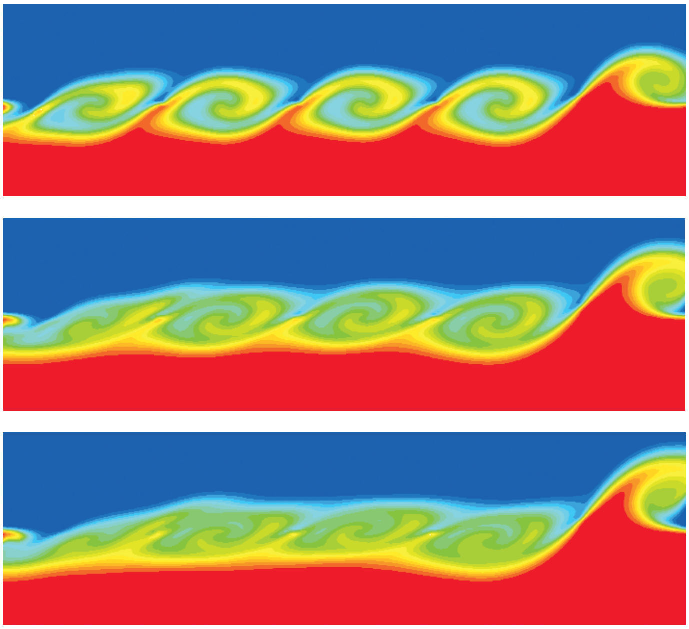


After 80 seconds, the Kelvin-Helmholtz cloud instability begins to break



The wave continues to roll after the break point, shown here after 135 (top), 175 (middle) and 195 (bottom) seconds; it eventually breaks up completely