Contrails

The picture of the jet condensation trail (shown below in Figure 1) was taken in Boulder Colorado around 5:30 pm on November 15th 2004. Figures 2 and 3 are other fascinating pictures of contrails that formed over the flatirons. The picture was taken from on top of the parking structure lot 436. The purpose for taking this image on top of the parking garage was to get an unobstructed view of the skyline above the trees and buildings. The purpose of the image was to get a picture of a jet condensation trail also known as a jet contrail. Jet contrails are usually abundant in the sky, particularly in the winter time. The goal of this project is to understand the formation of contrails behind an airplane.

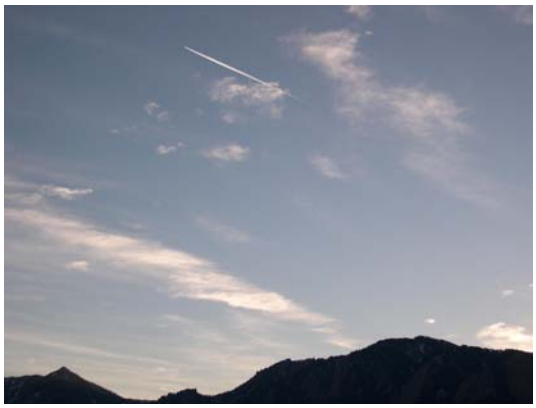

Figure 1. Jet Contrail (Southwest)

The flow in this picture is a condensation trail left behind a commercial jet airliner. Contrails are line-shaped clouds, considered to be cirrus clouds due to the height at which they are formed and the general shape or geometry of the cloud. Contrails are formed by two different types of processes. These two different types of contrail clouds are aerodynamic contrails, and engine exhaust contrails. The aerodynamic contrails are contrails that are formed by a momentary reduction in air pressure on top of the wing of a moving plane. This type of contrail is usually seen behind the wing tips of jet aircraft during a low-level airplane stunt show (like the Navy Blue Angles or the Air Force Thunderbirds). The aerodynamic contrail "consists entirely of atmospheric water that condenses as a result of local reductions in pressure due to the movement of the wing or propeller" [1]. A reduction in air pressure on the top of the wing is what is responsible for keeping the airplane in the air. The logical reasoning and scientific understanding of why there is a pressure difference between the top and bottom of the wing is not to difficult to understand from a general approach. A simple explanation involves following two streamlines: one that flows across the top of the wing, and one that flows beneath the wing. A small parcel following the top streamline travels a farther distance than a parcel flowing along the bottom streamline due to the shape of the wing. If the time for the parcels to travel their respective distances is the same, then the top parcel must have a higher velocity since the top parcel must travel a further distance. Bernoulli's equation states that the pressure plus the density multiplied by the velocity is a constant along a streamline. Therefore, if the velocity increases along a streamline, the pressure must decrease in order for Bernoulli's equation to equal a constant. Thus the parcel that travels along the top streamline has a lower pressure relative to the bottom of the wing because its relative velocity is higher than the parcel traveling along the lower streamline. If the fluid around the wing, in this case air, is assumed to be an ideal gas then if the pressure decreases with no change in volume then the temperature must decrease. Thus the formation of aerodynamic contrail is due to a local drop in pressure above the wing which may decrease the temperature enough to condense the moisture contained in the atmosphere. The second type of contrail is known as an engine exhaust contrail. These types of contrails are usually developed high in the atmosphere, "typically at aircraft cruise altitudes several miles above the Earth's surface" [1]. According to the Aircraft

Contrails Factsheet published by the EPA, persistent engine exhaust contrails are composed only by a small portion of water from the engine exhaust, the remaining moisture that forms the ice clouds comes from "water naturally present along the aircraft flight path" [1]. A persistent contrail is basically defined as a contrail that exists or grows, and "can last for hours while growing to several kilometers in width and 200 to 400 kilometers in height" [1]. If the atmospheric conditions do not favor contrail persistence, then the newly formed ice particles will quickly evaporate as the exhaust gases mix with the surrounding atmosphere resulting in a short visible contrail that extends only a small distance behind the aircraft.

Figure 2. Jet Contrial (West)

Figure 3. Jet Contrail (South)

Paoli et al. further elaborates on engine exhaust contrail formation by stating that "contrails consists of ice crystals which mainly form by condensation of exhaust water vapour at suitable nucleation sites, like soot particles and sulphur aerosols, emitted by aircraft engines" [2]. Water vapor is present in the engine exhaust because water is a combustion product when a hydrocarbon fuel is combusted or burned in the presence of air. The most common products in the engine exhaust due to combustion of hydrocarbon fuel in air includes: carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), unburned hydrocarbons, sulfur gases (sulfur is an impurity in the fuel), water vapor, and soot or small particles. Of these engine combustion products, according to the Aircraft Contrails Factsheet, "only water vapor is necessary for contrail formation" [1]. Basically, contrails would not form behind aircraft engines without the water vapor by-product present in the exhaust. But, small soot particles, or particles already present in the atmosphere are important as well because these small particles are the source for the nucleation sites necessary for the condensation of water vapor. In other words, "a contrail will form if as the exhaust gases cool and mix with the surrounding air, and the humidity becomes high enough (or, equivalently, the air temperature becomes low enough) for liquid water condensation to occur" [1]. Thus, contrail formation is a result of hot moist exhaust gases mixing with the cold less humid ambient air. Although, a cloud is usually formed heterogeneously, thus as stated before, small particles that act as nucleation sites are necessary for water to condensate into liquid droplets and thus freeze if the atmospheric conditions are suitable. The mixing of the moist exhaust gases with the ambient air is mainly attributed to trailing vortex formed from the aircraft's wings. Paoli et al. used a mixed Eulerian/Lagrangian two-phase flow model to predict the formation of a contrail. The fundamental model "consists of an exhaust jet, loaded with water vapour and soot particles, interacting with a wing-tip trailing vortex" [2]. According to Paoli, "an interesting extension to this work would be to analyse the interaction between an exhaust jet and a wing-generated vorticity sheet to find out how its turbulence further modifies exhausts dispersion and ice growth" [2]. Thus engine exhaust contrails are formed by hot moist engine exhaust mixing with the ambient air due to vortex structures from the wings. The mixing of these two gases leads to the condensation of the water vapor in the exhaust onto soot particles from the exhaust, or particles already present in the atmosphere. If the conditions in the atmosphere are suitable, then the condensed water vapor will freeze, and act as a nucleation site for further condensation from the atmosphere. In the end, if the contrail persists, or lasts a long time, most of the moister contained in the contrail consists of moisture already present in the atmosphere

In order to get useful information out of the photograph, some sort of length scale must be established. The picture of the jet contrail was taken at 5:27 pm. The sun was setting over the mountains, which illuminated the clouds and the contrail. From looking at the picture, the contrail is much brighter than the other clouds in the sky. Since the picture was taken around sunset, a logical conclusion is that the contrail is at a higher elevation than the clouds. Thus the plane is probably a commercial airliner flying from the west coast to Denver International Airport. Zooming in on the picture shows that the width of the contrail can be approximated as two times the wing span of the airplane. The wing span of a Boeing 737 is 28.35 m or approximately 93 feet (http://www.b737.org.uk/techspecsdetailed.htm). Likewise, the wing span of a Boeing 747 is 64.67 m or about 212 feet (http://www.aircraft-photos.net/Boeing_747_400.aspx). Using an average for these two wings spans, the unidentified airplane has a wing span of approximately 152.5 ft. Since the width of the contrail is approximately two times the wing span, then the width of the contrail is 305 feet. Now, since there is a value for the approximate width of the contrail, the contrail length can be deduced and is roughly 17,080 feet long or 3.23 miles in length. Furthermore, the field of view can be abstracted from this information. The field of view is in the region of 8 miles in height to 10.6 miles in width.

Below is a list of the camera settings, and some information about the photograph that will help define the picture.

- Field of View – As described above, by finding the wing span of the plane, the width of the contrail can be deduced. Then the size of the field of view can be inferred because a length scale has been established with respect to the width of the contrail. The field of view is approximately 8 miles in height by 10.6 miles in width.
- Distance from object to lens – Estimated to be 15 to 20 miles
- Camera Type
  - Nikon Coolpix 4300 (digital)
    - Resolution 4 Megapixels
- Lens
  - Lens Specifications
    - Focal length – 8 to 24 mm
    - Max Aperture – 1: 2.8 – 4.9
  - Focal Length – 12.2mm
  - Focus - Infinity
- Exposure
  - Aperture – F 3.4
  - Shutter speed – 1/538

This image reveals a jet contrail as the commercial airline passes over the Rocky Mountains. I really like the dark flatirons as the foreground, and the contrast from the dark blue sky in the upper left hand corner to the light blue sky just above the mountains highlighted by the setting sun. I also enjoy artistically how this image is not just a white streak contrail against a blue sky background, rather the flatirons, setting sun, and several white cirrostratus clouds enhance the image immensely. The physics revealed is the mixing of two gases by the passage of a jet airliner through the atmosphere. Also, the physics of condensation in the atmosphere, which is a common topic in cloud formation is discussed. More specifically the condensation of water vapor on nucleation sites (heterogeneous nucleation) is looked at, and is a common process for the formation of clouds. I would like to understand a little bit more about the modeling of mixing in a two phased flow. If I were to take on this project again, I would definitely use a zoom lens to get a closer view of the high altitude engine exhaust contrails.

References

[1] “Aircraft Contrails Factsheet” United States Environmental Protection Agency. EPA430-F-00-005 September 2000. http://www.epa.gov/otaq/regs/nonroad/aviation/contrails.pdf.

[2] Paoli, Roberto. Helie, Jerome. Et al. “Contrail formation in aircraft wakes” Journal of Fluid Mechanics. Vol. 502. pp. 361-373, 2004.