

# Drop-wise condensation: Experiments and simulations of water nucleation and growth in a cooling system



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## Introduction

When water condenses on a hydrophobic surface, a semi-ordered array of water droplets is formed, as on the plastic coffee cup lid shown at right. Such "dropwise" condensation produces higher heat transfer rates than "filmwise" condensation, and is of interest for heat exchangers and condensers. Understanding the formation of drops also has applications for waterproofing, meteorology (rain, dew), and adhesion. The formation and growth of liquid droplets on a solid surface remains incompletely understood.



We are approaching this problem along two lines: experimental observations and computer modeling. Unlike most previous computer models of condensation, our model is based on the physical processes involved (rather than simplified empirical models) and includes the nucleation of new drops as the simulation progresses.

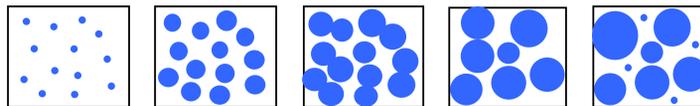
Most prior experiments and modeling have used constant temperature. However, many natural systems where dropwise condensation occurs have varying temperature, and in many cases condensation occurs as an initially hot system cools. To better understand these systems, we included an exponential temperature decrease in the computer model, and the initially hot water in the experiments was allowed to cool naturally.

Once the computer model has been calibrated to the experimental results, the model can be used to investigate the effect of changing various parameters, which may not be directly accessible experimentally.

## Stages in Droplet Evolution

Processes involved in dropwise condensation are:

- 1) Initial nucleation of drops on previously bare surface
- 2) Growth of drops
- 3) Coalescence of drops which grow large enough to touch each other
- 4) Additional nucleation of new drops in areas which become available due to coalescence (renucleation)
- 5) Loss of drops due to gravity (not included in current experiments)

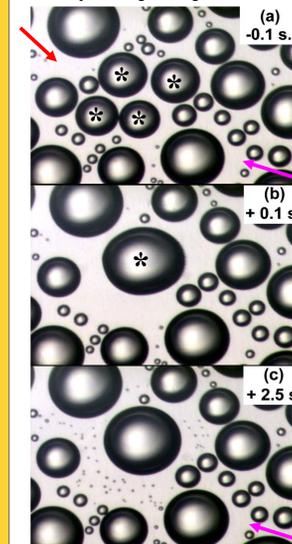


Stage I - growth      Stage II - coalescence      Stage III - renucleation

We modeled the initial nucleation as a random process (homogeneous nucleation). Droplet growth was modeled by an equation including contributions from vapor and from adsorbed molecules. Renucleation was modeled as either a random process, or as being linked to droplet coalescence.

## Renucleation

We initially assumed that renucleation was a random process which could occur in any area which had been cleared by coalescence. However, experimental observations revealed that renucleation did not appear to be random, but was closely associated with droplet coalescence. Coalescence not only provided the open space required for new drops to form, but also seemed to trigger the formation of new drops in neighboring areas.



In this sequence of images, four large drops (marked by asterisks in image a) and several smaller drops coalesce into a single larger drop (marked by an asterisk in image b). In image c many new drops are visible due to renucleation in the area opened up by coalescence. These drops became visible from 0.2-1.0 seconds after coalescence. Note that a nearby open area (red arrow in a) did not experience renucleation until the coalescence occurred, while a more distant open area (purple arrows in a and c) remained clear of renucleation.

Similar events were observed many times. Areas which appeared large enough to support renucleation remained empty until a nearby coalescence event occurred. After a coalescence event, renucleation occurred in the newly cleared area and also in nearby areas which had previously been cleared, including areas which did not appear to be directly linked to the coalescence event. Nearly all observed renucleation was associated with nearby coalescence events.

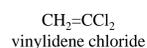
Using the computer model, we simulated renucleation both as random and as being associated with coalescence. However, the two models produced essentially similar results.

## Experiment

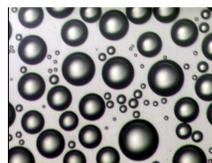
For the experiments, a film of Saran® wrap was stretched across a holder and placed over a beaker of water that had been heated to the desired temperature. A microscope above the film was used to observe and record the water drops that condensed on the film as the water cooled. Drops could be observed down to about 5 μm in diameter at the highest magnification, and video was captured at 30 frames per second.



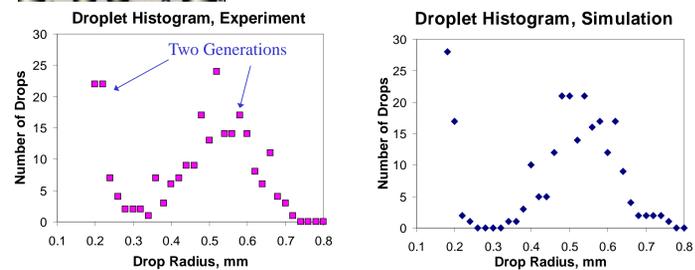
Saran® wrap is primarily poly(vinylidene chloride) and has a water contact angle of 58°.



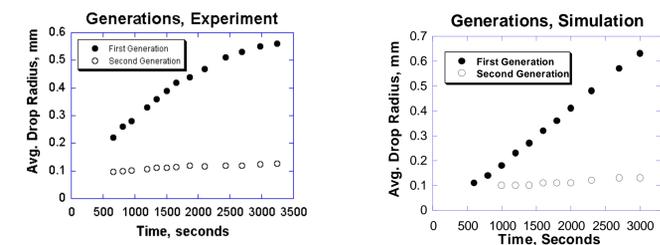
## Droplet "Generations"



Once a set of droplets has reached Stage III, two "generations" of droplets are observed. The larger drops have been growing and coalescing since the beginning of the experiment, while the smaller drops have nucleated later in spaces opened up by larger coalescing drops. The generations remain distinct, and no more than two generations have been observed.

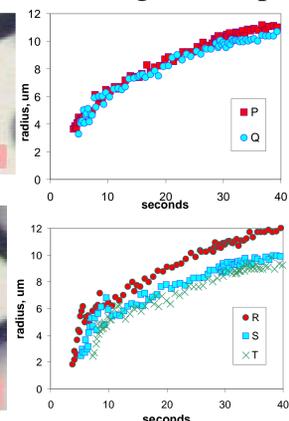
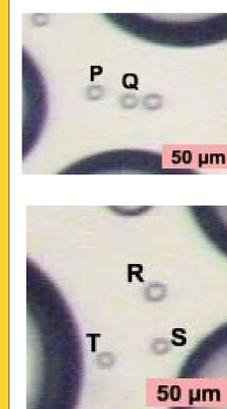


Our computer model successfully reproduced the observed "generations" of drops, both qualitatively and quantitatively.



The average radius for drops in each "generation" was also closely matched by the computer model. The average size of second generation drops grows very slowly, because the largest drops merge with first generation drops, while renucleation constantly adds very small drops to the second generation population. Note that the droplet generations become increasingly distinct as time progresses.

## Effect of Crowding on Droplet Growth

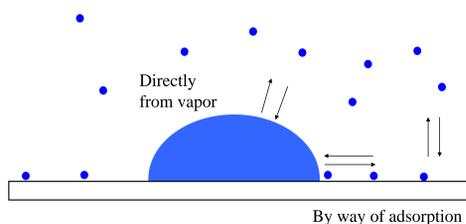


The effect of neighboring droplets was examined by measuring growth of droplets which nucleated together in slightly different environments. Droplets which were near other droplets were often observed to grow more slowly than droplets which were more isolated. However, the effect was small, and was not always observed. Each drop might deplete water vapor locally, leading to reduced growth rates of nearby competing droplets. If this is the case, the small variations observed means that the depletion zone around each drop must be small.

In these images, drops P, Q, R, S, & T nucleated at nearly the same time in two different locations after a coalescence event. Drop P was relatively isolated while drop Q was right next to another new drop, but drops P and Q showed nearly identical growth rates. In the other location, drop R was relatively isolated, while drops S and T were near existing larger drops. In this case, drop R grew somewhat faster than drops S and T.

Droplet growth has often been modeled as  $r \sim t^u$ . In fitting our drop measurements to this formula, we found for most small drops  $u \sim 0.5$ . However there was significant variation in  $u$  from drop to drop, possibly because of the effects of neighboring droplets.

## Modeling Droplet Growth

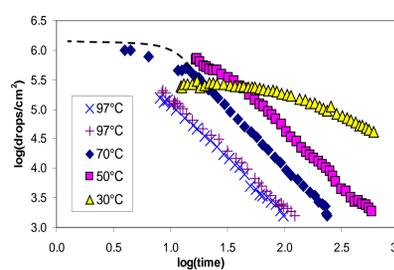


Droplet growth can happen in two ways: directly from the vapor, or via adsorption at the surface. Our equation for droplet growth includes terms for both contributions.

$$\frac{d}{dt} V(t) = F(t) (S(\theta) r(t)^2 \alpha + 2\pi r(t) \beta)$$

- First term is growth from vapor (proportional to drop surface area), second term is growth from adsorbed species (proportional to drop perimeter).
- $F(t)$  is flux of water molecules in the vapor
- $S(\theta)$  is drop surface area as a function of time and contact angle  $\theta$
- $r(t)$  is drop radius as a function of time
- $\alpha$  and  $\beta$  are constants which incorporate sticking probabilities, diffusion constants, etc.
- Since volume cannot be observed directly, the equation was converted into terms of drop radius. Kinetic theory was used to calculate the flux  $F(t)$ . Water molecules adsorbed at the surface were assumed to be in equilibrium with the vapor. No drop-drop interactions were considered in the model.

## Initial Nucleation Density



Drops formed initially are too small to be observed directly. If the density of first generation drops is measured as a function of time as the population is reduced by coalescence, the initial drop density can be extrapolated. For condensation over 97°C water initial densities of  $\sim 10^7$  drops/cm<sup>2</sup> are indicated. When the water temperature was reduced, the extrapolated initial density first increased (50°C or 70°C water) and then decreased (30°C water). Over 30°C water drops grew for a while without coalescing (Stage I behavior).

It seems likely that an initial period of droplet growth without coalescence (Stage I) also occurs at the higher temperatures, but is over by the time the drops are large enough to be observed. In this case, linear extrapolations will give inaccurate results. The actual initial drop density over 50°C or 70°C water is probably  $\sim 10^6$  drops/cm<sup>2</sup> (dashed line) rather than the extrapolated  $\sim 10^8$  drops/cm<sup>2</sup>.

## Conclusions

The computer model considering growth from both drop surface area and perimeter was able to reproduce most aspects of the observed droplet growth. However, the computer model still broadly reproduced the observed growth when modeling parameters were varied over a wide range. The main characteristics of dropwise condensation appear to be very robust, and are not dependent on certain specific conditions.

Initial nucleation densities over boiling water were extrapolated to  $\sim 10^7$  drops/cm<sup>2</sup> and Stage I behavior could not be observed. Reducing the source water temperature to 70°C or 50°C increased the extrapolated initial density, but did not change drop behavior. Further reducing the source water temperature to 30°C reduced the initial density to  $\sim 10^5$  drops/cm<sup>2</sup>, and slowed drop evolution enough that Stage I behavior could be observed. Stage I behavior probably also occurs at the higher temperatures.

Renucleation was not a random process, as expected, but was closely linked to drop coalescence. The reasons for this linkage are not yet understood.

Drops that were near other drops (more crowded) grew slightly more slowly than isolated drops. However, the difference was small and was not always observed. It is not clear what aspects of drop crowding lead to slower growth. The drop-drop interactions which lead to crowding effects may be related to the interactions which cause renucleation to be triggered by drop coalescence. Further experiments to study these effects are underway.