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# Steam condensation dynamics in annular gap and multi-hole steam injectors

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**Abstract**

In direct UHT (Ultra high temperature) treatment, milk is pumped through a closed system where it is preheated, high temperature heated, cooled, homogenised and packed aseptically [1].Continuous direct steam injection is used to quickly raise the temperature of a product, either for pure heating or for a sterilization process. The injector can be of either annular gap type (also called ring nozzle steam injector), or multi hole type. In this study we have analyzed the details of the condensation process by visualizations and by mapping the temperature fields. It was found that steam condensation in steam injectors is an intense process with heat transfer rates in the order of 1 MW/($m_2$ K). The steam is always condensed at the equilibrium temperature and the turbulence created in the condensation zone mixes the hot condensate and heated product with the cold product. The efficiency of this turbulent transport determines the sufficient heat transfer area and thus the size of the steam/product interface. If the condensation rate is faster than the steam addition rate the condensation process is unstable which results in detachments, fluctuations, noise and vibrations.


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*Keywords:* Steam injection; Condensation; Injector; Heating

## 1. Introduction

In direct UHT (Ultra high temperature) treatment, milk is pumped through a closed system where it is preheated, high temperature heated, cooled, homogenised and packed aseptically[1]. Continuous direct steam injection is used to quickly raise the temperature of a product, either for pure heating or for a sterilization process. The benefit of the direct contact condensation process is high heat transfer rates and low taste changes compared with other methods such as heat exchangers. The incoming product to the injector is preheated to approximately 80°C before entering the injector. In the injector the temperature is raised to about 140°C and pressures are held at >3.5 barg to prevent boiling. The product is held at this high temperature in approximately four seconds in the holding tube before it enters a expansion chamber where it is flash cooled. The flash cooling takes place in partial vacuum where the pressure is controlled

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so that the amount of vapour flashed off is equal to the amount of water added in the steam injection step [1].

The injector can be of either annular gap type (also called ring nozzle steam injector), Figure 1a) or multi hole type, Figure 1b). The annular gap type has two annular gaps; in this case, an inner gap for the product and an outer gap for the steam. The steam is thus injected coaxial in an angle into the product flow. The multi hole type consists of a manifold fitted in a cylindrical pipe section. The annular manifold is perforated with tiny holes, or nozzles, ordered in a row of holes in rings. Cold product is fed to the inside of the manifold as steam is supplied on the outside. The pressure on the steam side of the manifold is greater than in the product, resulting in steam flowing through the nozzles penetrating the product stream. The steam condenses as heat is transferred to the cold product. Condensate is mixed with the cold liquid raising its temperature further. The product finally leaves the injector at the desired temperature.

A critical issue in the design of steam injectors of the manifold type is how to ensure an even mixing and heating in the whole range of conditions appearing along the length of the injector. The goodness of mixing of cold and hot regions of fluid can be suspected to partly depend on the geometry of the hot steam surface available and the mementum induced by the penetrating steam. The question arises: – How deep and in what way will steam under given conditions penetrate into the product before enough heat is transferred away to make the steam undergo a phase change, condense and then mix with the ambient fluid?

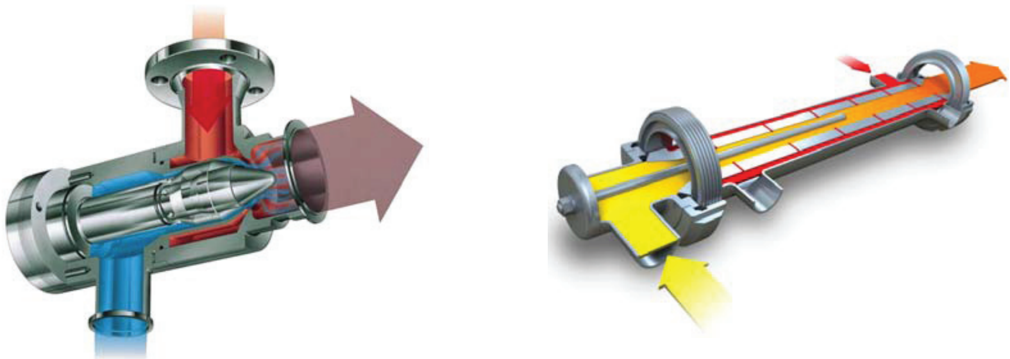

Fig. 1. Steam injectors; a) Annular gap type, b) Multi hole type [1]

## 2. Materials & Methods

Two main types of experiments was conducted, model 2D experiments and full scale 3D experiments.

To visualise the condensation in the annular gap type injector a 2D visualization injector was developed. The house and cover of the injector was hollow and glass plates, acting as channel walls, made observations of the condensation process possible. The geometry of the channels was designed with plastic inlays that defined the channel flow through it. Figure 2 displays a cross section of the real injector and the half cross section that the plastic inlays were designed from.

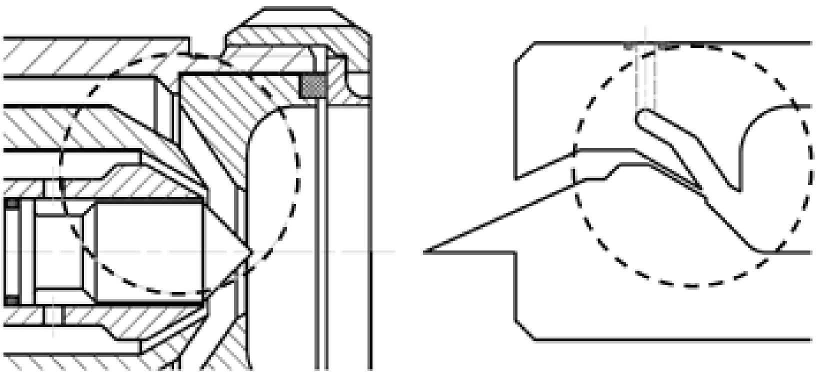

Fig. 2. Comparison of geometry of the annular gap injector and the plastic inlays

In the real injector the steam jet converges from the annular opening and meets in the middle. As there is no possibility of two jets that meet in the experimental injector the plastic piece is designed so no steam can pass the symmetry line from the cone in the injector. This restrain of flow represents the meeting jet that occurs in the real injector.

To investigate the condensation process, a full scale (5000 l/h) steam injector was used in its standard configuration heating product from 80 to 142°C. It was fitted with two different holding cells, one with a measurement section, and one experimental in glass, used for visualization experiments, both with an inner diameter of 60 mm. The measuring section holds four thermocouples, A-D (Figure 3). The thermocouples were placed to cover the region from where the initial mixing of the phases occurs to where most of the steam was condensed. A is the thermocouple reaching into the outlet channel, B is the one almost touching the tip of the injector. Thermocouples C and D is mounted perpendicular to the injector and the other thermocouples, at distances approximately 27 and 47 mm from the steam seat. The thermocouples can be traversed along their axes. The measuring piece is attached to the injector with 12 bolts and can thus be rotated with angular steps of 30°. In this work, the measuring piece was rotated in steps of 90°.

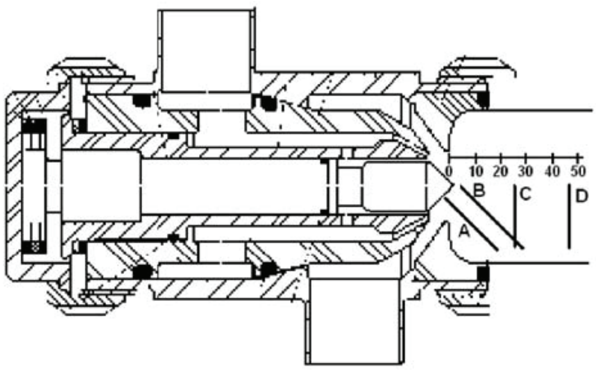


Fig. 3. The positions of the thermocouples (A-D). Dimmensions in millimeters

In the multi hole case a visualization injector was designed to mimic the geometry of the real steam injector. A sketch of the geometry of the manifold in the real injector is shown in Figure 4 A and B. The design of the plastic inlays was limited to consist of a single nozzle and a product channel with a rectangular cross section. This was done to reduce the complexity of the situation at expense of the similarity of the real injector. A sketch of the region at the nozzle is shown in Figure 4 C. The nozzles were made out of brass in five different diameters ranging from 0.5 to 1.9 mm. Steam pressure upstream the nozzle is kept constant at 5.6 barg. The pressure ratio was varied at six levels ranging from 0.91 to 0.23 giving steam mass fluxes in the range 400 to 750 $kg/sm_2$. The water temperature was varied at different levels from 10 to 95°C to span a subcooling interval ranging from 20 to 140°C in steps of 10°C.

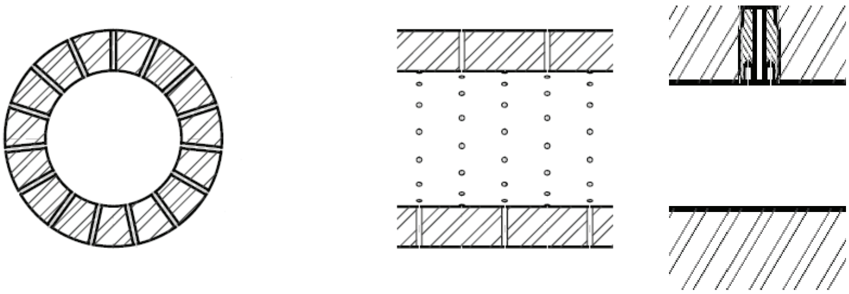

Fig. 4. A,B) Geometry of a section of the manifold in the real injector, C) One nozzle model injector

## 3. Results & Discussion

### *3.1 2D model of Annular gap injector*

At constant heat transfer, the heating rate is the inverse of the heating area, in this case the jet length. It was found that the jet length varies with the following parameters

1. Heating or steam flow. Increasing the steam flow increases the steam velocity and the steam penetrates further into the slow moving water in the mixing chamber.
2. Holding cell pressure. Increasing the pressure reduces the volume of the steam and with it the steam velocity. It also increases the sub cooling increasing the condensation rate. Both effects decrease the jet length.
3. Capacity or product flow rate. Increasing the capacity increases both the product and the steam flow and velocity. The increase in product velocity seems to increase the mixing and increase the condensation rate. The increase in steam velocity is to week to counteract this and the jet length decreases.

The oscillations of the jet are related to the jet length, the longer jet the larger extent of oscillations. As jet length is shortened, more condensation occurs per unit volume, resulting in higher noise levels. The estimated heat transfer coefficient ranges from 0.2 to 2 $MW/(m_2 K)$ in the experiments. The coefficient is increased at higher pressures as the jet length is shorter. The heat transfer is also increased as the velocity of the water and steam is increased, as the turbulence levels are increased favouring higher heat transfer.

In figure 5 one can observe two different mixing regions in the condensation zone; A week mixing and condensation region between the steam and the hot water with low velocity in the mixing chamber, and an intense mixing and condensation region between the steam and the cold water flowing along the lower wall.

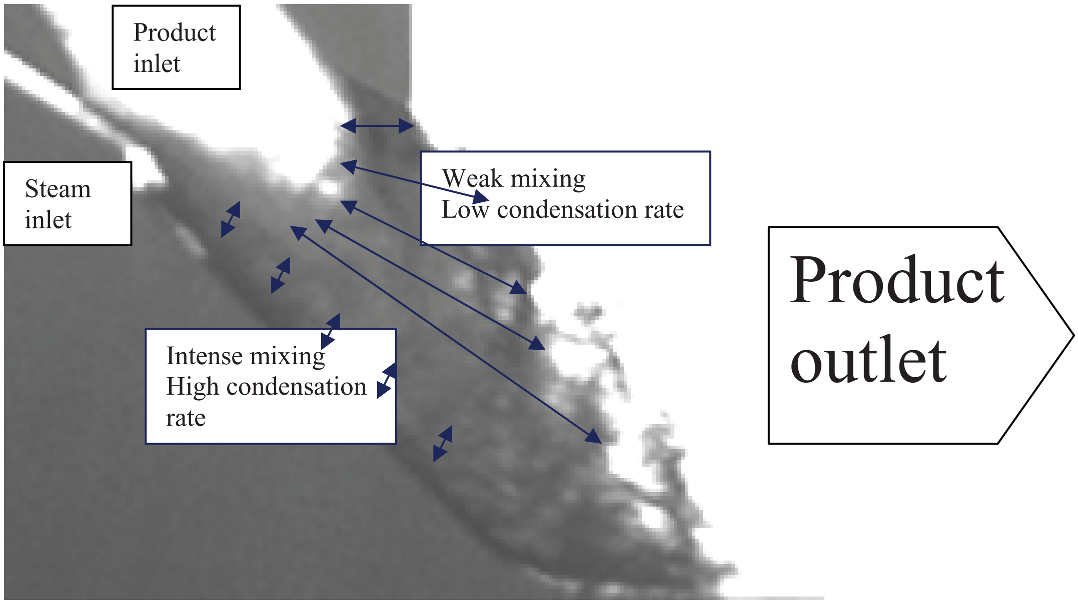


Fig. 5. 2D Steam condensation zone

### *3.2 Full scale annular gap injector*

Figure 6 show the steam jet 30-130 mm downstream of the injector. The condensation rate is very high and the steam jet condensation and collapse creates intense turbulence. The length of the condensation zone is less than two pipe diameters

Fig. 6. 3D Steam condensation zone

The average temperatures of the temperature probes penetrating into the steam can be seen in Figure 7. The product is heated up to 142ºC, and that is also the temperature far from the steam jet. The inner probes reach into the cold core where the temperature is that of the incoming product, 80ºC. The steam cavity and the newly condensed steam hold the saturation temperature, in this case 152ºC. Most of the condensation takes place in the thin zone between the hot steam and the cold incoming product.

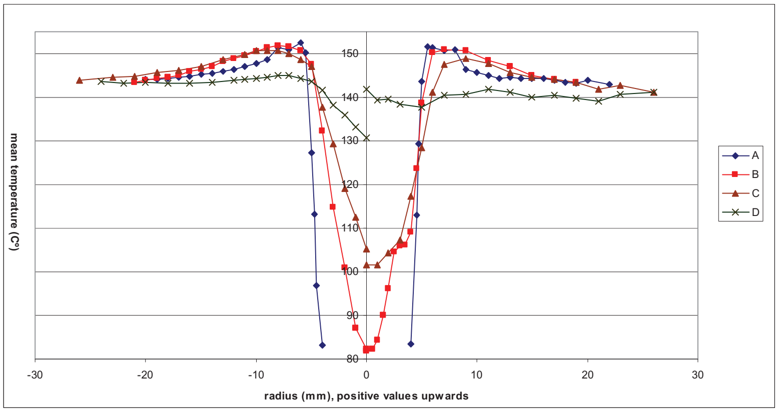


Fig. 7. Average temperature readings from the four temperature probes as they are traversed into the steam jet

### *3.3 Single hole steam condensation*

Two classes of steam condensation regimes ware found. The first class, jetting, is characterized by only one connected steam cavity of small deviation from symmetry around the axis of the nozzle. The second class, cavity formation, is characterized by more irregularly shaped bodies of condensing steam and multiple disconnected cavities (Figure 8).

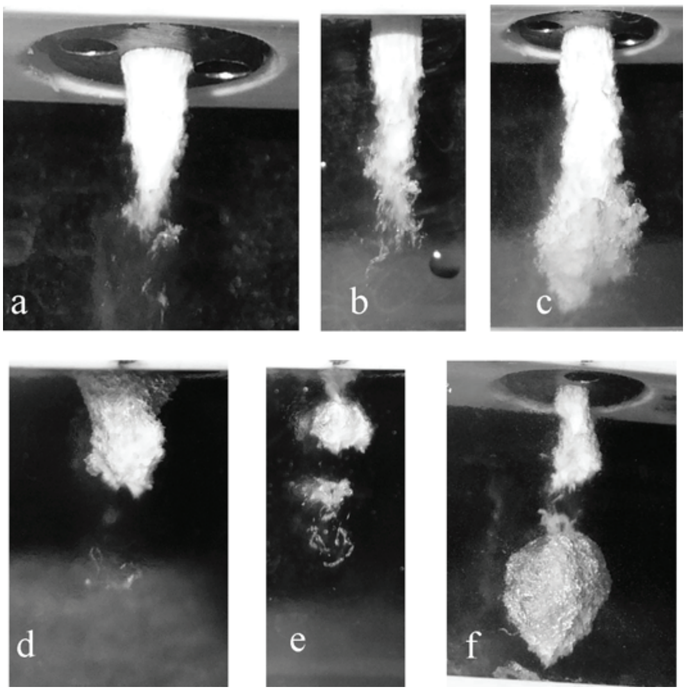


Fig. 8. Regimes: a) Conical jetting, b) Ellipsoidal jetting, c) Divergent jetting, d) Single cavity formation, e) Cavity detachment, f) Jet detachment

The regime class jetting can be divided into three regimes: Conical, ellipsoidal and divergent jetting (as suggested by [2] whereas the regime class cavity formation can be divided into single cavity formation, cavity detachment and jet detachment.

A regime map can be found in Figure 9. It is evident that regimes under cavity formation are the dominating ones when steam flow is non-choked and steam velocities are lower. Single cavity formation appears at high subcooling since heat transfer rates are high enough to allow steam to condensate at a rate high enough so that that the interface stays in one piece. If the subcooling is lowered cavities start to detach. The different forms of jetting are only detected under conditions where steam mass fluxes are high. Conical jets appear at high subcooling. If the temperature of the water approaching the steam-water interface is increased further ellipsoidal jets develop. At low subcooling the jet detaches.

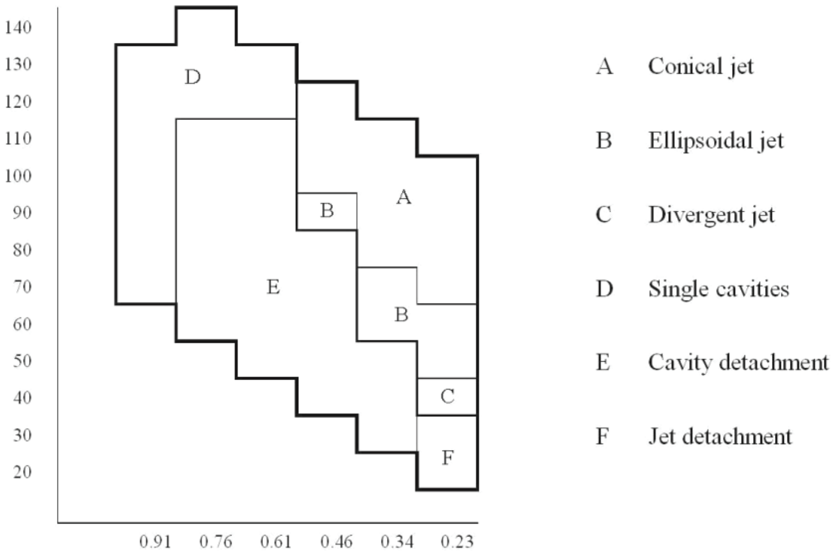


Fig. 9. Regimes observed when varying subcooling and steam flow

## 4. Conclusion

Steam condensation in steam injectors is an intense process with heat transfer rates in the order of 1 MW/($m_2$ K). The steam is always condensed at the equilibrium temperature and the turbulence created in the condensation zone mixes the hot condensate and heated product with the cold product. The efficiency of this turbulent transport determines the sufficient heat transfer area and thus the size of the steam/product interface. If the condensation rate is faster than the steam addition rate the condensation process is unstable which results in detachments, fluctuations, noise and vibrations.

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[2] Chun, Kim, Park, 1996, An investigation of direct condensation of steam jet in subcooled water, Int. comm.. Heat mass transfer Vol. 23, No. 7.

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