ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

FAKULTA STROJNÍ

Ústav mechaniky tekutin a termodynamiky

TEORIE ROZPADU KAPEK V CHLADÍCÍ VĚŽI SE SPLASH VÝPLNÍ

THEORY OF WATER DROPLETS BREAKDOWN IN THE COOLING TOWER WITH SPLASH FILL

Bakalářská práce

Studijní program: Teoretický základ strojního inženýrství

Vedoucí práce: Ing. Pavol Vitkovič, Ph.D.

Jan Papoušek

Praha 2017

ČESKÉ VYSOKÉ UČENÍ TECHNICKÉ V PRAZE

ZADÁNÍ BAKALÁŘSKÉ PRÁCE

I. OSOBNÍ A STUDIJNÍ ÚDAJE

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II. ÚDAJE K BAKALÁŘSKÉ PRÁCI

Název bakalářské práce:

Teorie rozpadu kapek v chladici veži se splash vyplní

Název bakalářské práce anglicky:

Theory of water droplets breakdown in the cooling tower with splash fill

Pokyny pro vypracování:

1. Proveďte řešerši v oblasti grid (splash) výplní používaných v chladicích věžích s ohledem na mechanizmy přenostu tepla a hmoty,
2. Pokuste se vytvořit model Gridové výplně z pohledu přenosu tepla a hmoty

Seznam doporučené literatury:

Incropera, Frank P., DeWitt, David P.: Fundamentals of heat and mass transfer
Kroger, D.: Air-cooled heat exchangers and cooling towers.

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III. PŘEVZETÍ ZADÁNÍ

Student bere na vědomí, že je povinen vypracovat bakalářskou práci samostatně, bez cizí pomoci, s výjimkou poskytnutých konzultací. Seznam použité literatury, jiných pramenů a jmen konzultantů je třeba uvést v bakalářské práci.

28.4.2017
Datum převzetí zadání

Podpis studenta

CVUT-CZ-ZBP-2015.1

Anotační list

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Anotace: Tato práce přináší krátký úvod o chladících věžích, jejich typech, vnitřním složení a principu vypařovacího chlazení. Jsou zde uvedeny mechanismy tvorby vodních kapek spolu s existujícími měřeními a teoriemi uvedenými různými autory. Součástí je také základní matematický model a výpis jevů, které je nutno dále zkoumat.

Abstract: This work brings a brief introduction on cooling towers, their types, structure, and principles of evaporative cooling. Mechanisms of droplet creation mechanisms are stated along with existing measurements and theories provided by various authors. A basic mathematical model and a summary of phenomenons that require further investigation are also stated.

Čestné prohlášení

Prohlašuji, že jsem tuto práci vypracoval samostatně a pod odborným vedením vedoucí práce Ing. Pavola Vitkoviče, Ph.D.

Dále prohlašuji, že všechny použité podklady jsou uvedeny v seznamu použité literatury

V Praze dne 24. 5. 2017

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Jan Papoušek

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At last, let me state a great thanks to my family for their financial aid during my whole studies and my girlfriend for her mental support during my work on this thesis.

CONTENT

NOMENCLATURE

Symbol	Quantity	Unit
a	absolute humidity	kg/m^3
d	diameter	m
f	ratio	-
g	gravitational acceleration	m/s^2
m	mass	kg
$\dot{m}$	mass flow	kg/s
n	number of droplets	-
v	velocity	m/s
x	specific humidity	kg/kg
C	drag coefficient	-
L/G	water/air loading ratio	-
Q	heat	J
T	temperature	°C
V	volume	m^3
W	width	m
We	Weber number	-
δ	water film width	m
λ	wave lenght	m
μ	dynamic viscosity	Pa.s
ρ	density	kg/m^3
σ	surface tension	N/m^2
φ	relative humidity	%

Subscript	Meaning
a	air
c	cutting
con	convective

d	dripping
e	evaporation
f	satellite
g	gas
i	input
l	liquid
o	output
s	splash
sat	saturated air
vp	water vapor
w	water

1 INTRODUCTION

1.1 Thesis purpose

The aim of this work is to gather information about cooling towers with a special focus on fills, including characterization of commonly used fills and describing heat and mass transfer mechanisms appearing on splash and grid fills. A simple model describing thermomechanical processes on fills is also part of this thesis.

1.2 Methodology

The procedure of writing this work starts with a search in available literature about cooling towers, documents of companies involved in cooling tower business, and basic literature on heat and mass transfer fundamentals. These resources will be used to fulfill the main purpose of this thesis-describing types of used fills in cooling towers and thermomechanical procedures on fill layers. The main search is about droplet creation mechanisms, measurements, and theories provided by other authors. A basic model that takes advantage of search is designed.

1.3 Introduction to cooling towers

The cooling tower is an industrial facility that can be found in power plants and other industrial and chemical factories. Its purpose is to cool circulating water and release the heat into the atmosphere. As an example of cycle including cooling tower can be considered nuclear power plant (see Figure 1.0). Steam is produced in the order to turn the turbine, thus turning an electric generator and generating electricity. Steam then flows into a condenser where heat exchanges and steam condenses back into water thanks to cold water in another circuit. This water has to be cooled in the cooling tower before being used in the condenser again [1]. This mechanism is essential for correct work of a whole facility, therefore a profound understanding of inner processes inside cooling tower is necessary as it could lead to better-designed towers and energy and cost savings [2]. In past, the warm water used to be released back to the local environment (e.g. lake and river close to the facility). This caused damage to fauna and flora and is now unacceptable [3, 4]. In past, cooling tower and its parts were usually made of wood. The benefit of using timber structure was lower initial costs. However, damage caused by alkalis, oxidizing agents, and organisms such as fleshy fungi caused a short lifetime of the structure up to 10 years while maintaining inspection of unbearable rot, mold or disease spread [5].

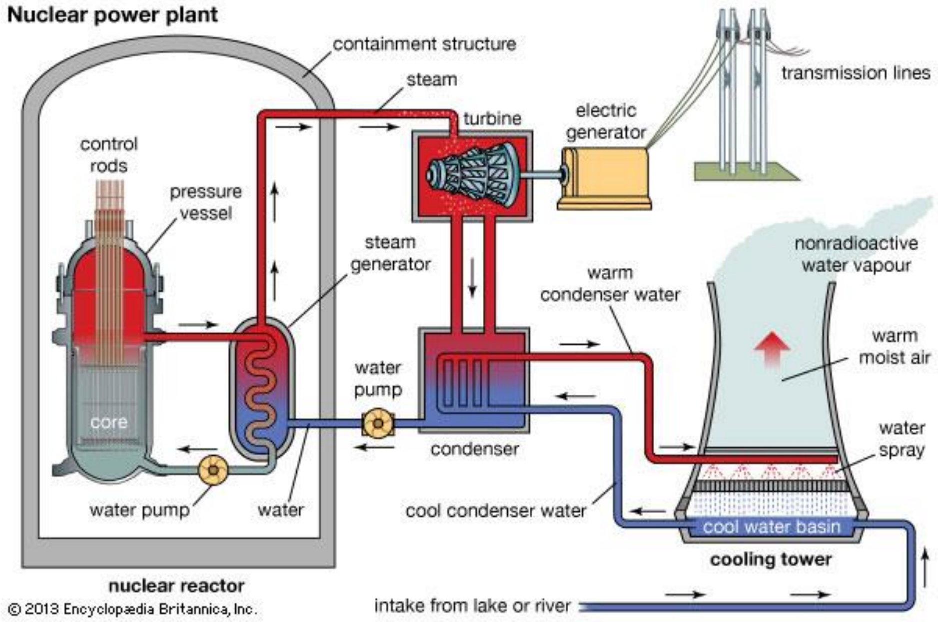

Figure 1.0 Nuclear power plant scheme [6]

2 COOLING TOWERS OVERVIEW

2.1 Types of cooling towers

Cooling towers can be categorized by many specifications (such as type of applied heat transfer, direction of water and airflow, mechanism of creating airflow draft, shape of chassis).

Characterization of heat transfer

- **Wet cooling towers** – In the wet cooling towers, water comes in direct contact with airflow. Heat is transferred thanks to water evaporation (so-called evaporative cooling) and convective heat transfer.
- **Dry cooling towers** – In the dry cooling towers, warm water flows in tubes that are exposed to ambient air and water is cooled without direct contact of water and air thanks to convection and radiation.
- **Hybrid cooling towers** – Hybrid cooling towers are combination of wet and dry cooling towers. The ambient air cools water in direct contact as in wet tower and before leaving into the atmosphere, it flows around tubes filled with hot water and convective heat transfer takes place (see Figure 2.0). This process takes advantage of fact that air leaving the wet cooling tower has lower temperature than the hot water input and still has some cooling potential [7].

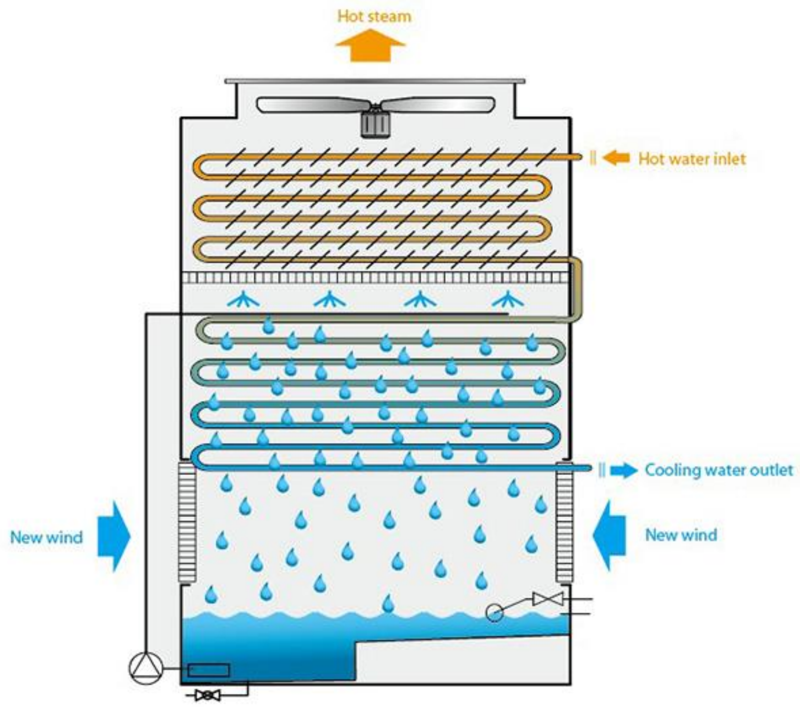

Figure 2.0 Hybrid cooling tower scheme [8]

Characterization of air and water flow direction

- **Counterflow cooling towers –** Water falls down from the top of the tower thanks to the gravitation force and airflow is forced/draught parallelly from entering the bottom to the top (see Figure 1.3).
- **Crossflow cooling towers** – Water falls down from top of the tower similarly to the counterflow type. However, the airflow enters from sides of the tower and leaves at the top (see Figure 2.1). Because of an outlet air recirculation, this type of tower is considered as less effective and also has higher operation costs than the counterflow type [7].

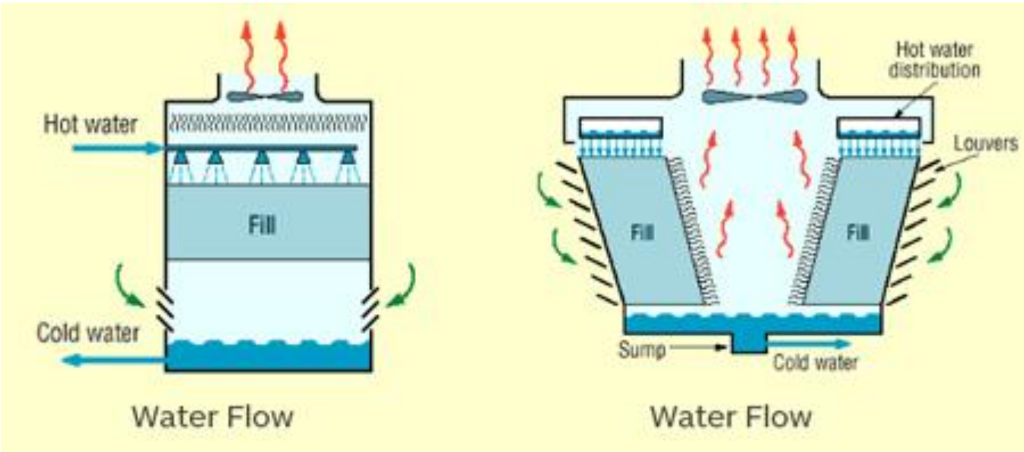

Figure 2.1 Counter- and crossflow tower [9]

Characterization of air draft

- **Natural draft cooling towers –** These towers are of hyperbolic shape, around 100 m high. Air flows from bottom to the top thanks to the difference in air density outside and inside of the tower. As air in the tower entrance is warmed by water, it has a higher temperature than the ambient air at top of the tower. Higher temperature means lower density, which leads to airflow from bottom to top of the tower. These towers are preferred for larger installation (e.g. power plants above 500 MW), require higher initial costs but provide lower operation and maintenance costs compared to mechanical draft towers [7].

- **Forced mechanical draft cooling towers –** These towers are generally lower than those with the natural draft and air velocities are higher thanks to fan that generates the draft. The fan is located at the bottom of the tower providing the highest velocity of air there.
- **Induced mechanical draft cooling towers –** These towers are similar to the forced mechanical draft ones but the fan is located at the top of the tower, therefore, creating highest velocity there.

2.2 Parts of the counterflow wet cooling tower with induced draft

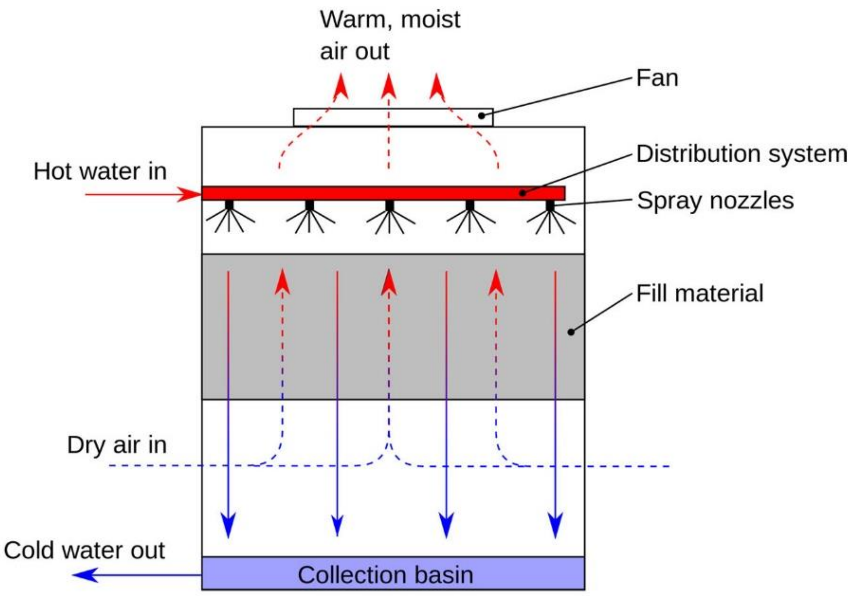

Figure 2.2 Cooling tower diagram [10]

Cooling tower’s components are located inside a metal chassis (see Figure 2.2). The fan is located at the top of the casing providing airflow through the tower. As [11] suggests, an empirical formula can be used to calculate the necessary power of the fan as each 226,5 m^3/min of air is equal to 1 horsepower≈0,75 kW.

The pipes with hot water entering the tower can be seen below the fan. Water is sprayed in form of droplets across the inner area through distribution nozzles creating so-called spray zone. At the bottom of the tower, cooled water is collected in a basin and pumped to the other facility part where it serves its purpose, e.g. for the condenser. Because some portion of water discharges from the tower and evaporates, a make-up water is used as compensation so the water mass flow remains constant.

At the top of the tower, drift eliminators are located (see Figure 2.3). The purpose of this component is to reduce the amount of water that could be driven with the airflow out of the tower. Water droplets encounter these curved paths of plates and as they congregate, their mass eventually overcomes the force of airflow and water falls down back to the cooling tower and no water is driven by airflow out of the tower. Usually, from 0,008 to 0,0005 % of water is lost due to leaving the tower with airflow [12].

The main body of the tower contains of fills that are used to maximize heat transfer surface between water and air while minimizing a restriction of creation that could lead to a lower airflow rate. This part of the tower is known as fill zone, where the part below it is called rain zone. There are two main types of fills: film and splash. Film fills are plastic blocks of tubes where air, as well as water flow, takes place (see Figure 2.4). Water droplets from the nozzle are transformed into water film that ensures maximum area where heat and mass transfer take place. These fills rely on sufficient water and air mass flow rate as well as uncontaminated water [12]. Splash fills can be found as blocks-sometimes called trickle fills (see Figure 2.5) or bars-sometimes called grid fill (see Figure 2.6). These fills break up water droplets to create new droplets and a layer of water film is created on the slats [13]. The material used for fills must be also taken into consideration. Study shows that using *high surface energy – wetting* surface such as rigid polyvinylchloride (RPVC) leads to higher thermal performance than using a *low surface energy – nonwetting* material such as polypropylene (PP) [14].

Figure 2.3 Drift eliminator [15]

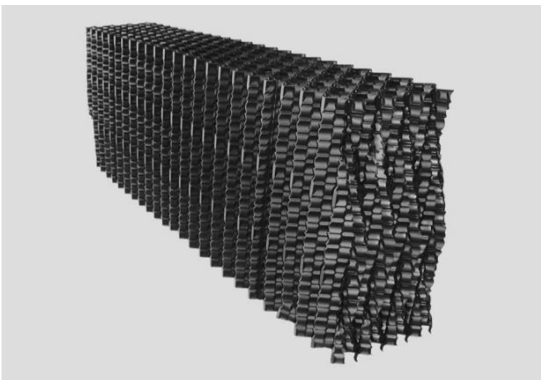

Figure 2.4 Film fill [16]

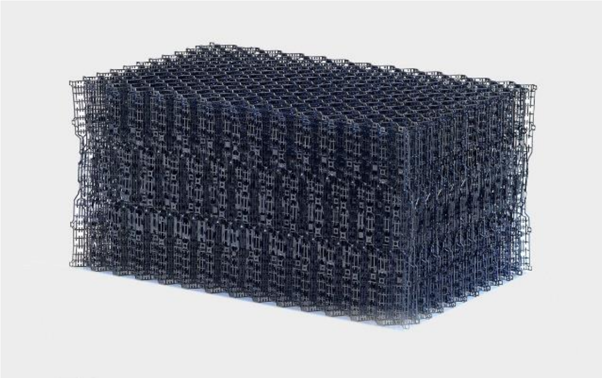

Figure 2.5 Splash fill block [17]

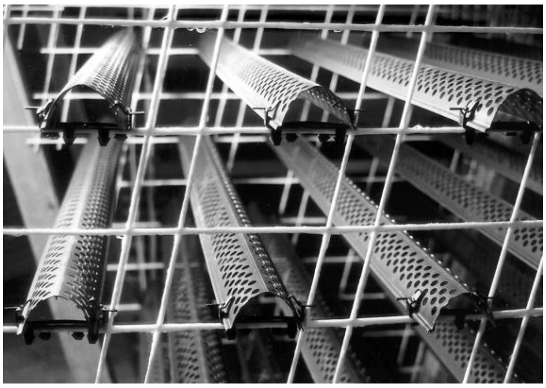

Figure 2.6 Splash fill V-bar [18]

2.3 Physical principle of cooling water

Humid air consists of dry air and water vapor. We can describe the amount of water in the air with some quantities. Absolute humidity a is a ratio of the mass amount of water vapor m_{vp} in a volume of humid air V and depends on the temperature [19].

$$a = \frac{m_{vp}}{V_a} \tag{1.1}$$

Relative humidity φ_a is a ratio of absolute humidity ρ_a to its maximum amount ρ_a'' at given temperature [19].

$$\varphi_a = \left(\frac{a_a}{a_{sat}}\right)_T \cdot 100 \tag{2.2}$$

When relative humidity is below 100 %, we can talk about unsaturated air. Air with 100% relative humidity is known as saturated air.

When hot water comes into contact with cooler air, two mechanisms of cooling water are happening simultaneously. One of them is known as the evaporative cooling. It can only occur for a relative humidity of air φ_a lower than 100 %. Water in form of droplet is surrounded by a thick layer of saturated air at the temperature of the water that comes in contact with unsaturated airflow in the cooling tower. Because of the difference in moisture content, some portion of water evaporates to the unsaturated air to get closer to an equilibristic condition. When this happens a form of energy known as latent heat of evaporation is released from water to air which leads to cooling the water and heating the air [3].

The second principle of heat transfer is due to the difference in water and air temperature, known as convective heat transfer.

It is assumed that 75-85 % of heat transfer is due to evaporative cooling while remaining 15-25 % is due to convectional heat transfer [20,21].

According to [11] the amount of water that actually evaporates f_e is estimated as 1 % of the whole circulation rate for each 5,56 °C of cooling. It can be also calculated as

$$f_e = \frac{x_o - x_i}{L/G} \cdot 100 \tag{2.3}$$

as a percentual part of the whole circulating water with the knowledge of fill *L/G* ratio or according to [22] with knowledge of air mass rate $\dot{m}_a$ as

$$\dot{m}_e = \dot{m}_a \cdot (x_o - x_i) \tag{2.4}$$

According to [3], the most important area of heat transfer is the fill as 80-90 % of the cooling tower performance is located in fill zone. 10-20 % of total transferred heat is in the rain zone when only a few percent of heat exchange performance is located in the spray zone.

We can neglect heat transfer from radiation and write total transferred heat as

$$Q = Q_{con} + Q_e \tag{2.5}$$

where Q_{con} is the convection heat transfer and Q_{ev} is heat transfer due to evaporation.

2.4 Statistic tools in cooling towers topic

Authors very often refer to cumulative mass distribution, for instance Rosin-Rammler distribution and Sauter mean diameter.

Cumulative mass distribution for droplet diameters is a statistical function that expresses probability that certain or smaller diameter occurs. [23]

Rosin-Rammler distribution curve is a plot of the Rosin-Rammler function that is

$$R_{RR}(d) = e^{-\left(\frac{d}{\bar{\bar{d}}}\right)^{\overline{n_{RR}}}} \tag{2.6}$$

where $\bar{\bar{d}}$ is a mean diameter that is obtained from measurement at which the cumulative mass distribution equals $R_{measured} = e^{-1}$ and $\overline{n_{RR}}$ is so called mean spread parameter, taken as average of spread parameters for drop diameter interval as

$$n_{RR} = \frac{\ln(-\ln(R_{measured}))}{\ln(\frac{d}{\bar{\bar{d}}})} \quad (2.7)$$

Authors usually involve calculated and measured parameters in tables at their work. [23]

Sauter mean diameter d_{32} describes average droplet size, therefore as diameter of droplet that would have the same volume and surface as the whole range of droplets and can be calculated as

$$d_{32} = \frac{\sum n \cdot d^3}{\sum n \cdot d^2} \quad (2.8)$$

References to Rosin-Rammler function and Sauter mean diameter as statistically acceptable form of interpreting results are proposed in [13]. However further investigation made by [23] showed that Rosin-Rammler doesn't fit for larger droplet diameters and is recommended by authors to be avoided (see Figure 2.7).

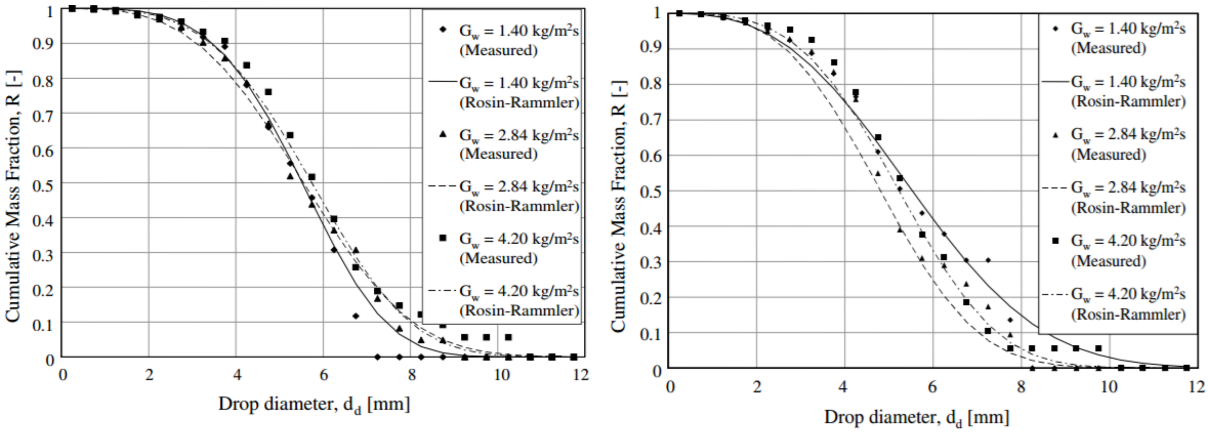

Figure 2.7 Mass distribution function and Rosin-Rammler distribution for trickle fill for m_a=1,22 kg/m^{2}s (left) and m_a=2,85 kg/m^{2}s (right) [23]

3 WATER BEHAVIOR IN COOLING TOWERS WITH SPLASH/GRID FILLS

When a water droplet impacts the surface of filling material that is covered by a water film layer, three different mechanisms of creating a new droplet can occur – splashing, cutting and dripping (see Figure 3.0).

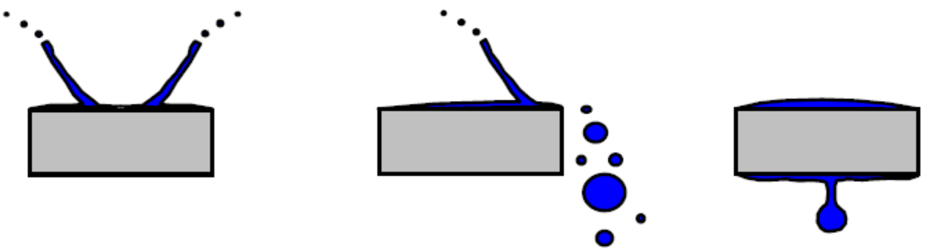

Figure 3.0 Drop formation mechanisms [13]

3.1 Splashing

When a water droplet hits water film on the fill, the film is pushed out and above the impact area forming a so-called *crown* made of many small droplets that leave the impact point at high velocity. The cavity created at the impact point eventually collapses, followed by so-called Rayleigh jet that strikes above the impact point (see Figure 3.1). According to [24], the height and number of drops of Rayleight jet for thin water film layers decreases as the film width decreases and can disappear for thin layers. According to [25] the mass of small drops created by the crown is a function of water film thickness and initial drop size. The splash ratio which is portion of water leaving the impact point m_{sT} to the mass of incoming droplet m_{iT} traveling at terminal velocity can be evaluated as

$$f_s = \frac{m_{sT}}{m_{iT}} = C_1 + C_2 (\frac{\delta}{d} - \frac{\delta}{4}) \tag{3.1}$$

where δ is the water film width $0{,}1<\delta<18$ mm and d is droplet diameter $2{,}96<d<5{,}6$ mm and

$$C_1 = 1 + 2{,}02 \cdot e^{-2{,}56 \cdot \frac{\delta}{4}} - 3{,}02 \cdot e^{-16 \cdot \frac{\delta}{4}} \tag{3.2}$$

$$C_2 = -0{,}2 - 13{,}6 \cdot e^{-2{,}87 \cdot \frac{\delta}{4}} + 60 \cdot e^{-18{,}63 \cdot \frac{\delta}{4}} \tag{3.3}$$

If f_s>100 %, the mass of water leaving bar is bigger than the incoming water droplet with the extra water being supplied from the water film.

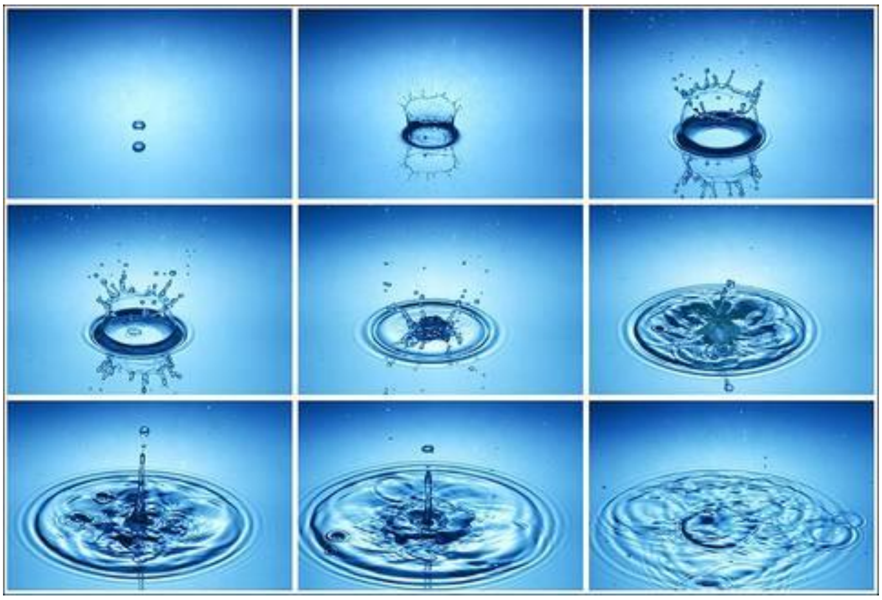

Figure 3.1 Water droplet impact evolution [26]

For impact velocities below terminal velocity v_t was the mass leaving the fill m_s found as an approximately linear function of mass leaving the fill at terminal velocity by [27] (see Figure 3.2)

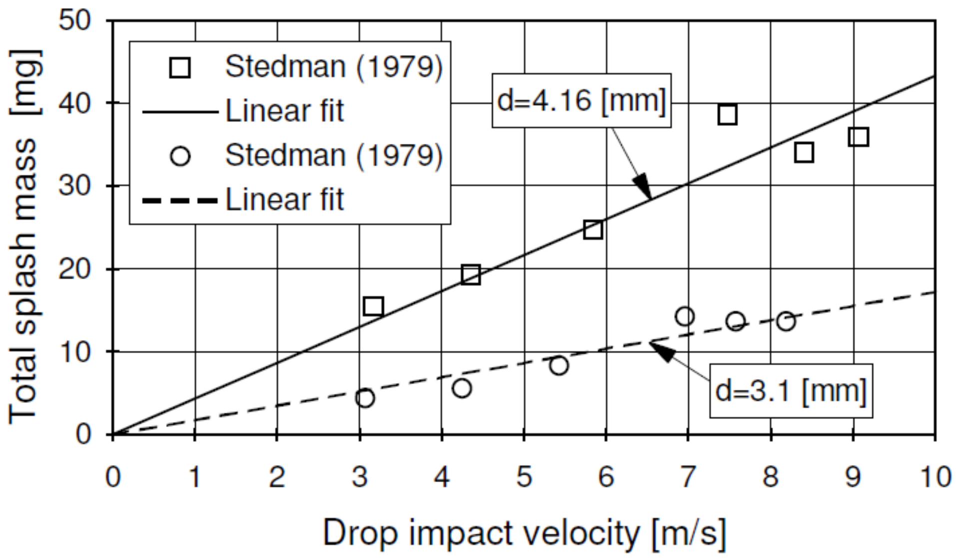

Figure 3.2 Splash mass as function of drop impact velocity [13]

$$m_s = m_{sT} \cdot \frac{v_s}{v_{sT}} \tag{3.4}$$

Where according to [28] the terminal velocity v_{sT} can be calculated as

$$v_{sT} = \sqrt{\frac{4 \cdot g \cdot d \cdot (\rho_w - \rho_a)}{3 \cdot \rho_a \cdot C}} \tag{3.5}$$

where C is the drag coefficient of the water droplet.

It can be noted that mass of the water droplets created by splash mechanism depends on initial water droplet diameter, water droplet velocity and water film width on the surface. For a model, evaluating size distribution of drops see [29].

According to measurement realized by [13], the splash fraction of splashing droplets for various impact velocities and impacting droplet diameter can be correlated using Rosin-Rammler distribution function. However, the equations would exceed the range of this work, as an illustration, are included two graphs showing the expected splash fraction (see Figure 3.3 and Figure 3.4). Note that for 1 mm thick water film smaller droplets didn't perform a splashing mechanism as they did for 0,5 mm thick water film.

In measurement done by [30], splash fraction up to 350 % was registered for certain initial nozzles distribution height (2,6 m of free fall of the droplet) and water supplement on the slat that created water film (0,9÷1,1 g/s).

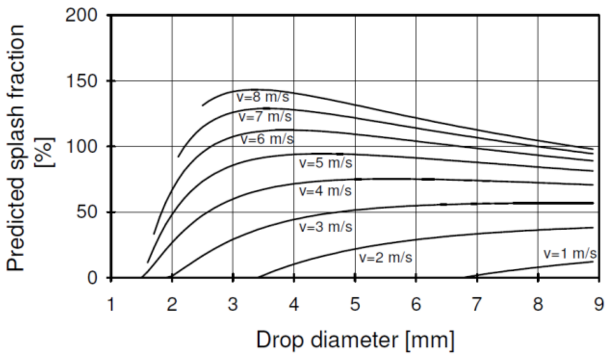

Figure 3.3 Predicted splash fraction for various drop diameters and impact velocities for 25 mm wide slat and 0,5 mm thick water film [13]

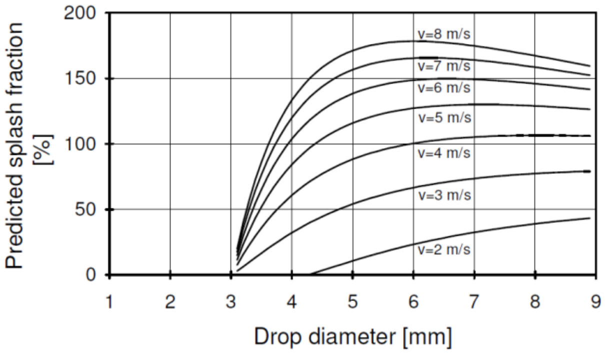

Figure 3.4 Predicted splash fraction for various drop diameters and impact velocities for 25 mm wide slat and 1 mm thick water film [13]

3.2 Cutting

The cutting means that droplet hits the edge of fill and is divided into smaller droplets. According to the measurement taken by [31] on drops of various diameters striking an edge of the bar, for impact point being 3-4 drop diameters from the edge the portion of mass that left the plate was 20 %, for impact point 0,5 diameters from the edge the losses increased to 80- 90 %.

According to study made by [32] that involved droplets impacting thinner strips than the drop diameter, a link between cutting mechanism and Weber number was found. Weber number is used to describe ratio of inertia forces to tension forces [33]

$$We = \frac{\rho_w \cdot v^2 \cdot d}{\sigma} \tag{3.64}$$

For Weber number below critical Weber number, the cutting didn't take place. On the other hand, when the Weber number was higher than the critical Weber number the droplet was always cut. The critical Weber number is associated with a critical diameter of the drop, that determines whether or not the drop can be cut into smaller drops as it is highly associated with the surface tension of a droplet. The study also found that the average drop size created by cutting is almost independent of Weber number. The velocity of drops formed by cutting is approximately the same as the initial drop velocity [13]. The critical Weber number is dependent on Ohnesorge number *Oh.*

$$Oh = \frac{\mu}{\sqrt{\rho \cdot \sigma \cdot d}} \tag{3.7}$$

For a known Ohnesorge number we can calculate the critical Weber number We_c [34]

$$We_c = 12 \cdot (1 + 1{,}007 \cdot Oh)^{1{,}6} \tag{3.8}$$

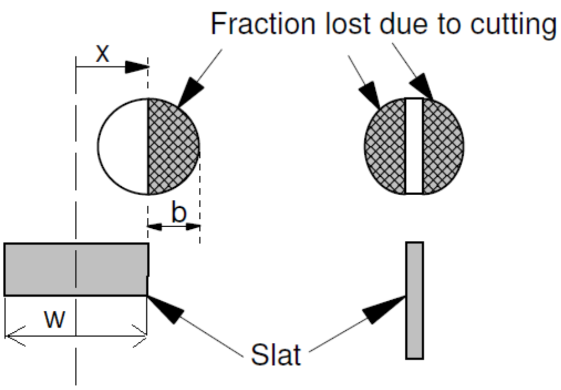

Figure 3.5 Cutting process [13]

The water mass leaving the edge due to cutting can be calculated as

$$m_c = \rho_w \cdot \left(\frac{\pi \cdot b^2}{3} \cdot \left(\frac{3 \cdot d}{2} - b \right) \right) \tag{3.95}$$

where

$$b = \left(\frac{2 \cdot x - W}{2} \right) + \left(\frac{d}{2} \right) \tag{3.106}$$

For the middle of a droplet striking directly at the edge (x=W/2), half of the droplet mass will be lost due to cutting, for x=(W-d)/2 cutting will not take place (see Figure 3.5). For a drop that is cut into two drops with similar mass in case of a drop striking a narrow slat where $d>W$, the mean diameter of each drop will be 0,79d. This diameter also applies for drop with diameter $d>W$ that hits the edge of the bar [13]. According to measurement done by [32] can be seen a big portion of drops created by cutting that have a diameter from 0,7 to 0,9 times to the original drop (see Figure 3.6). Only a slight dependence on Weber number was observed. Authors expressed size of droplets generated by cutting as

$$\frac{d_c}{d} = 0{,}8522 + 1{,}6 \cdot 10^{-5} \cdot We \tag{3.11}$$

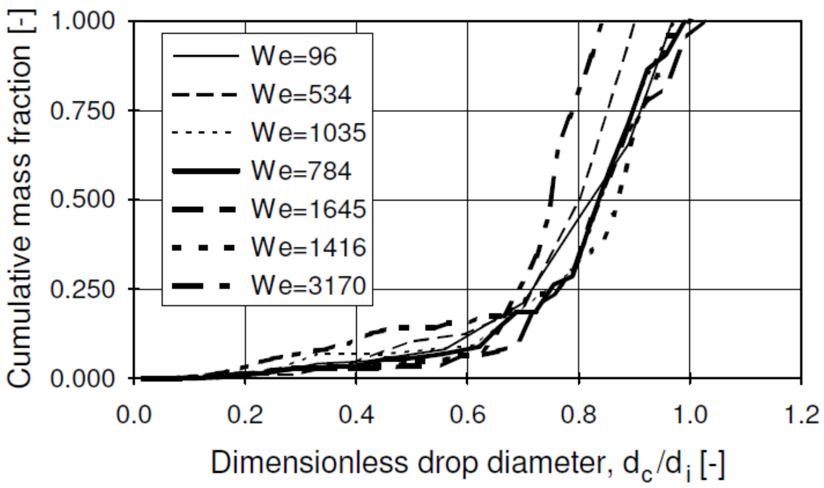

Figure 3.6 Drop diameter created by cutting compared to the original drop diameter [13]

3.3 Dripping

Another mechanism of creating new water droplets is dripping. These droplets drip from the bottom of bars or slats, created by water film that flows on the structure. The size of drop depends on surface tension and can be written as

$$d_d = K \cdot \sqrt{\frac{\sigma}{g \cdot (\rho_w - \rho_a)}} \tag{3.12}$$

where *K* is constant that contains a dependency on the geometry of the dripping surface and water flow. For horizontal surface dripping and constant water flow can be taken *K*=2,7÷3,3 [30].

When a *primary droplet* drips, one or more subsequent drops called *satellite drops* with diameter d_f follow. According to [35] the diameters of primary and satellite drops could be described as

$$0{,}24 < \frac{d_f}{d_d} < 0{,}46 \tag{3.13}$$

When the water flow is increased, instead of dripping one droplet after another, the *column mode* is initialized. A water column is created at the bottom of the slat that eventually breaks and forms new droplets. From the column instability theory can be calculated that these droplets have a diameter about 1,89 times of the column diameter [36].

The drop diameters dripping from flat slat are larger than those dripping from V-angle shaped slat. Another interesting note is that the mean diameter is smaller as the flow rate rises [37]. The drop diameter was found to be dependent on the slat geometry in measurement done by [13]. The drops had a bigger diameter when dripping from flat slats compared to the sharp-edged slat. A similarity to drops dripping from a nozzle is suggested, where the diameter of drops depends on nozzle size. A *shape factor* is defined that can be calculated from slat geometry and can be used as a correlation for *K* constant to determine the drop size diameter.

Interaction between heavier fluid (water) and lighter fluid (vapor) is related to the Taylor instability (see Figure 3.7). When droplets drip, the distance between dripping points is determined by wavelength that can be calculated as [38]

$$\lambda = 2\pi \cdot \sqrt{\frac{3 \cdot \sigma}{\rho_l \cdot g}} \tag{3.147}$$

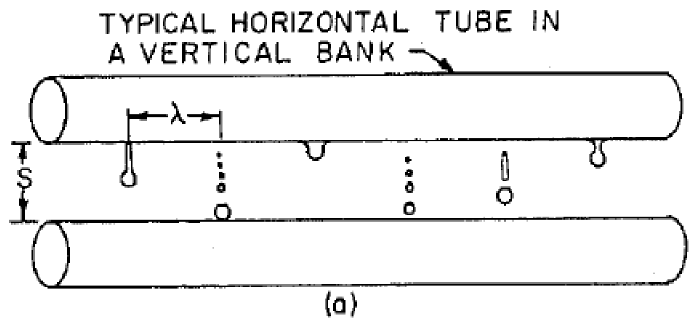

Figure 3.7 Taylor instability [38]

3.4 Droplets instability

The drop can become unstable if the forces coming from airflow disrupt the surface tension of a droplet. To become more stable, the droplet is divided into smaller drops as each of them has higher surface tension. The instability is determined by [39] as for We>11, the drop is considered to be unstable and the dividing mechanism will take place.

Droplets do collide with each other, taking the stochastic and probability methods into the problem. More can be found at [40] and [30].

As water droplets evaporate, their mass and diameter are influenced. For estimated 2 % of all water evaporated, a reduction of 0,7 % in diameter is assumed. According to [30] the shrinking may vary, as smaller droplets are expected to achieve higher diameter reduction.

3.5 Example of droplet size reduction

Authors in [23] suggest installing a slat grid below the fill to reduce water droplets diameter in rain zone. They perform a measurement with no airflow and a grid made of 3 mm slats with 10 mm spacing with Sauter mean diameter above the grid of 5,19 mm. The droplets are measured 260 mm below lowest grid with a fixed distance 60 mm between grids if more than one is used. Authors investigated the effect of distance between the set of grids and fill and found the smallest Sauter diameter of 2,47 mm for two grids at 0,8 m below the fill. When using airflow, only a slight change in this value to 2,48 mm was measured (see Figure 3.8). [23]

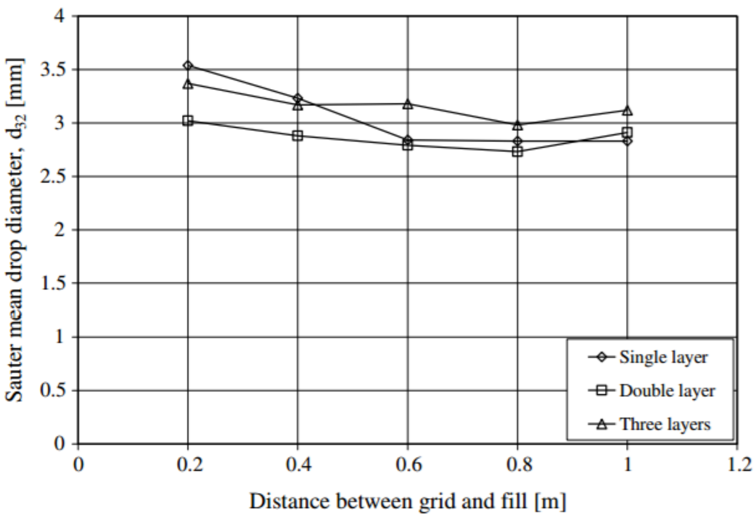

Figure 3.8 Sauter mean diameter for variable distance between grids and trickle fill for m_w=2,84 kg/m^{2}s [23]

Grids that performed as stated were made of narrow parallel slats with a space between them. When grids were made of slats in X-position (see Figure 3.9), overall performance changed dramatically. For the same water mass ratio and no airflow, Sauter mean diameter below this grid was 5,19 mm. This effect was caused by high number of nodes, where dripping performed. [23]

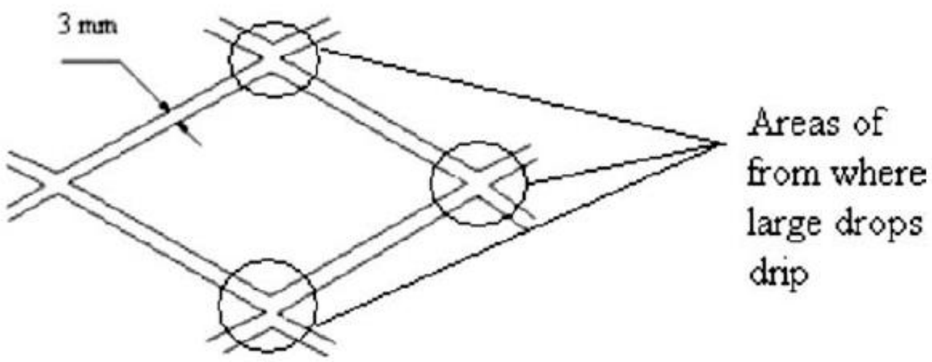

Figure 3.9 A scheme of grid with X-positioned slats. [23]

3.6 Water film

Measurement done by [30] assumes that water film area on the grid is small compared to the area provided by droplets in one layer. Surfaces as $A_{film} < 5$ m^2/m^3 and $A_{drops} > 100$ m^2/m^3 are stated. The water film thickness was measured with expected accuracy up to 0,05 mm. The data for 25 mm wide slat, water mass ratio 15 200 kg/m^{2}h (that means 106 g/ms on the slat) are included (see Figure 3.10)

Thickness of water film for Re < 1500 can be calculated with equation given by [41] as

$$\delta = (\frac{3 \cdot \mu \cdot m}{\rho^2 \cdot g})^{\frac{1}{3}} \quad (3.158)$$

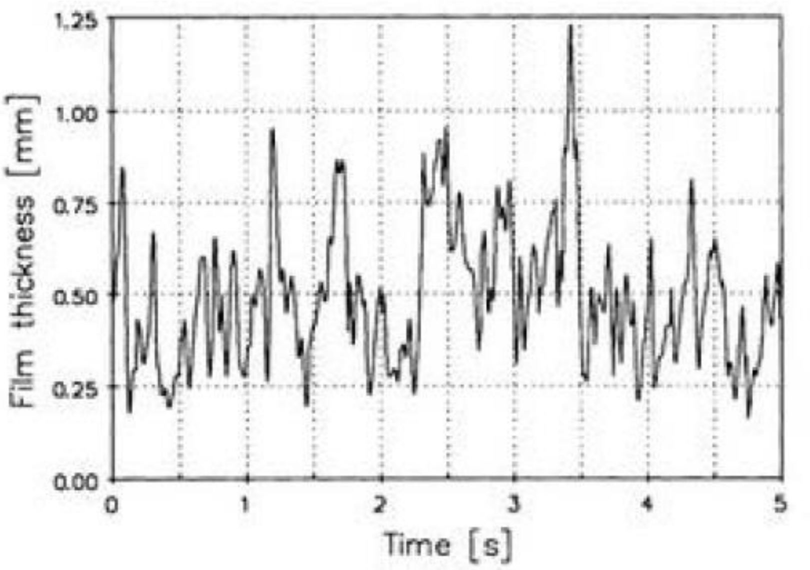

Figure 3.10 Film thickness for defined conditions [30]

Water film thickness is influenced by air velocity. Tests done by [41] for water flow rate 0,2 kg/(ms) showed a rapid increase in water film thickness once the velocity of air v_a=5 m/s is exceeded (see Figure 3.11). For v_a=2,3÷5 m/s was used a linear fit as water film thickness can be calculated as

$$\delta = 0{,}31649 + 0{,}01384 \cdot v_a \quad (3.169)$$

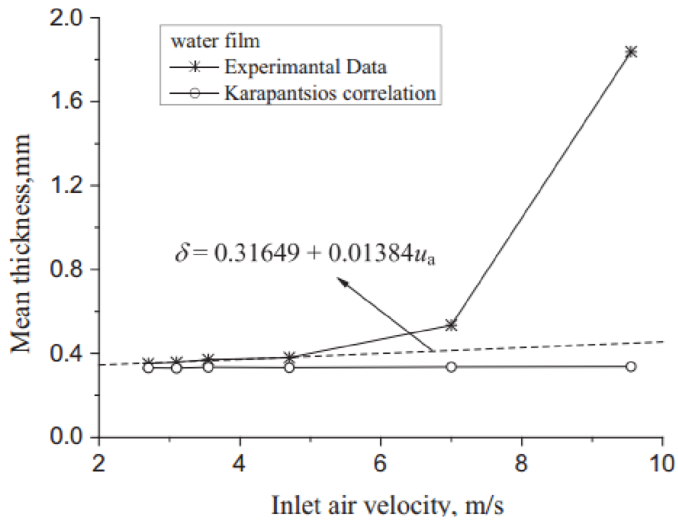

Figure 3.11 Dependance of film thickness to air velocity [41]

4 MATHEMATICAL MODEL

This model describing behavior of water droplet in cooling tower is a slight modification of the one provided by Ing. Tomáš Hyhlík, Ph.D. as used in [43]. The model describes change in velocity, diameter, and temperature of a statistical package of droplets depending on the purpose of droplet creation mechanism between two grid layers while also evaluating residence time and heat transfer. Droplets are divided into four groups: splashing, cutting, dripping and falling through.

Following assumptions are made:

- **Falling through** droplets represent 70 % of total water mass flow. These droplets fall through space in fills and are unaffected by any of droplet creation mechanisms as stated above. Initial droplet diameter is 10 mm, simulating a nozzle at the top of the tower. By the time they reach the top of the layer, their velocity is 3 m/s.
- **The cutting** mechanism is performed by 5 % of total water flow, their velocity starts at same as the falling through droplets – 3 m/s and diameter is calculated as if 10 mm droplet would perform cutting, using Equation 3.11 stated in Chapter 3.2 leading to diameter of 8,6 mm.
- **Splashing** mechanism is performed by 15 % of droplets, their velocity starts close to 0 m/s and initially generated diameter is 3 mm.
- **The dripping** mechanism is performed by 10 % of droplets, their velocity starts close to 0 m/s and initial diameter is calculated, using Equation 3.12 stated in Chapter 3.3 leading to an 8,13 mm.

Initial conditions of model:

- The height of layer is 0,3 m.
- The initial temperature of water droplets is 40 °C, air temperature is 15 °C with relative humidity $\varphi = 50$ %.
- Atmospheric pressure is 98 000 Pa
- Air mass flow is 15 000 kg/s, total water mass flow is 18 000 kg/s.

Model is ready to be used in research field after providing new starting conditions and could be improved heavily after investigating phenomenons stated in Chapter 5.

As an illustration of model implication, see Figure 4.0 that shows increasing velocity of droplets, Figure 4.1 that shows decrease in droplet radius, Figure 4.2 that shows decrease in water droplet temperature due to heat and mass transfer, Figure 4.3 that shows residence time – time that water droplet stays in between layers and finally Figure 4.4 showing heat being transferred by various mechanisms.

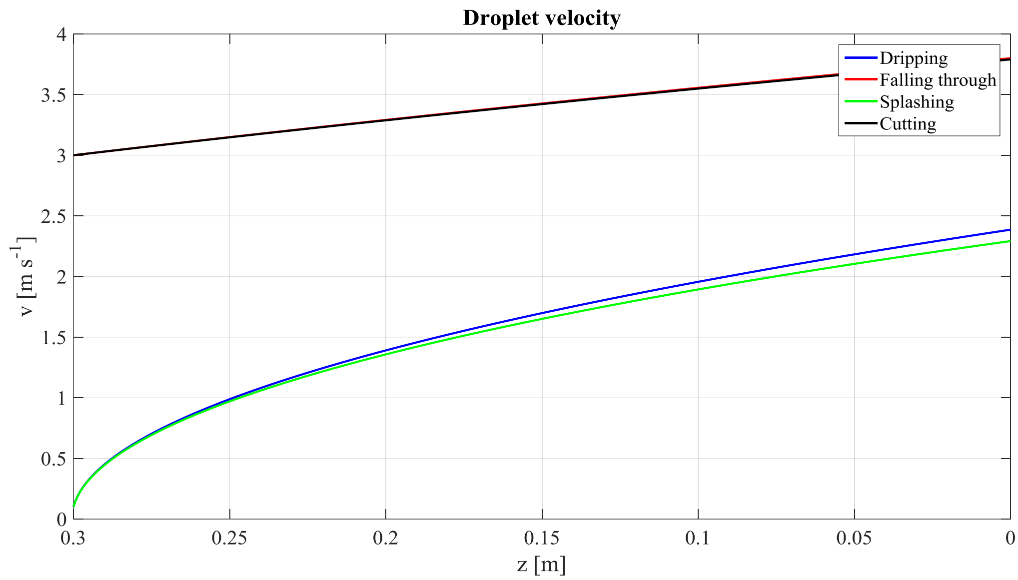

Figure 4.0 Droplets velocity

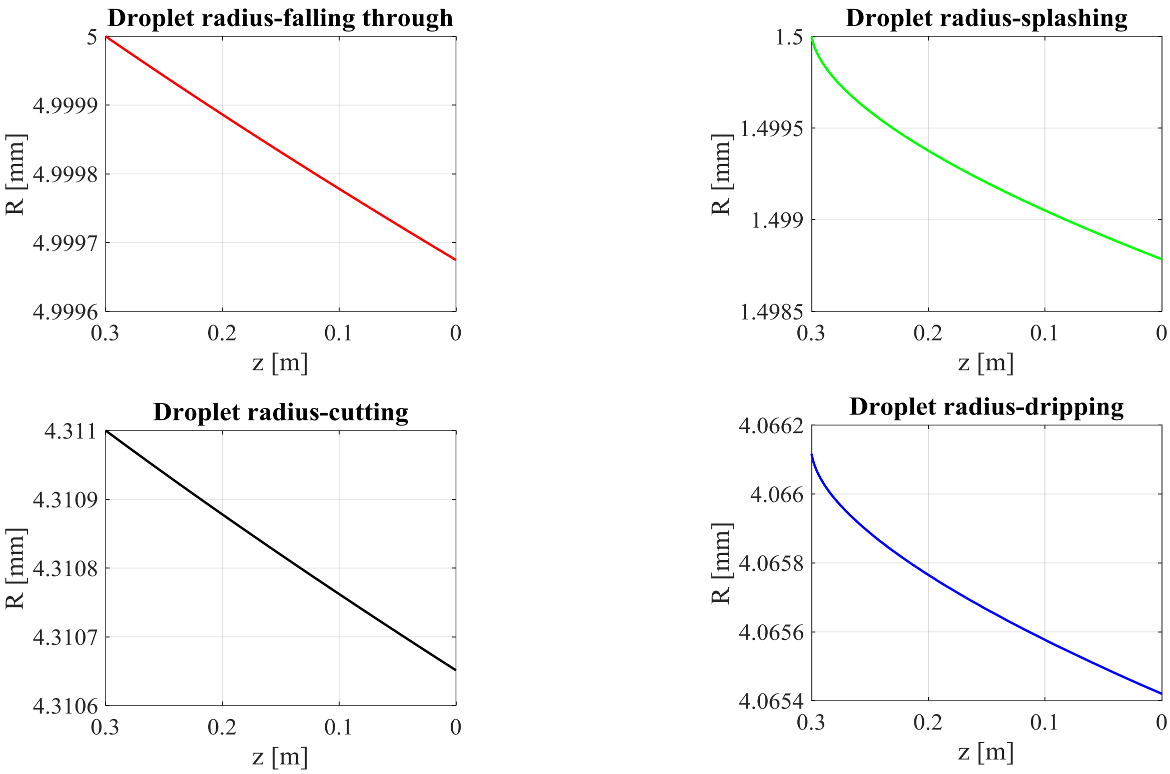

Figure 4.1 Droplet radius decrease (showing all mechanisms in one graph wouldn't be legible)

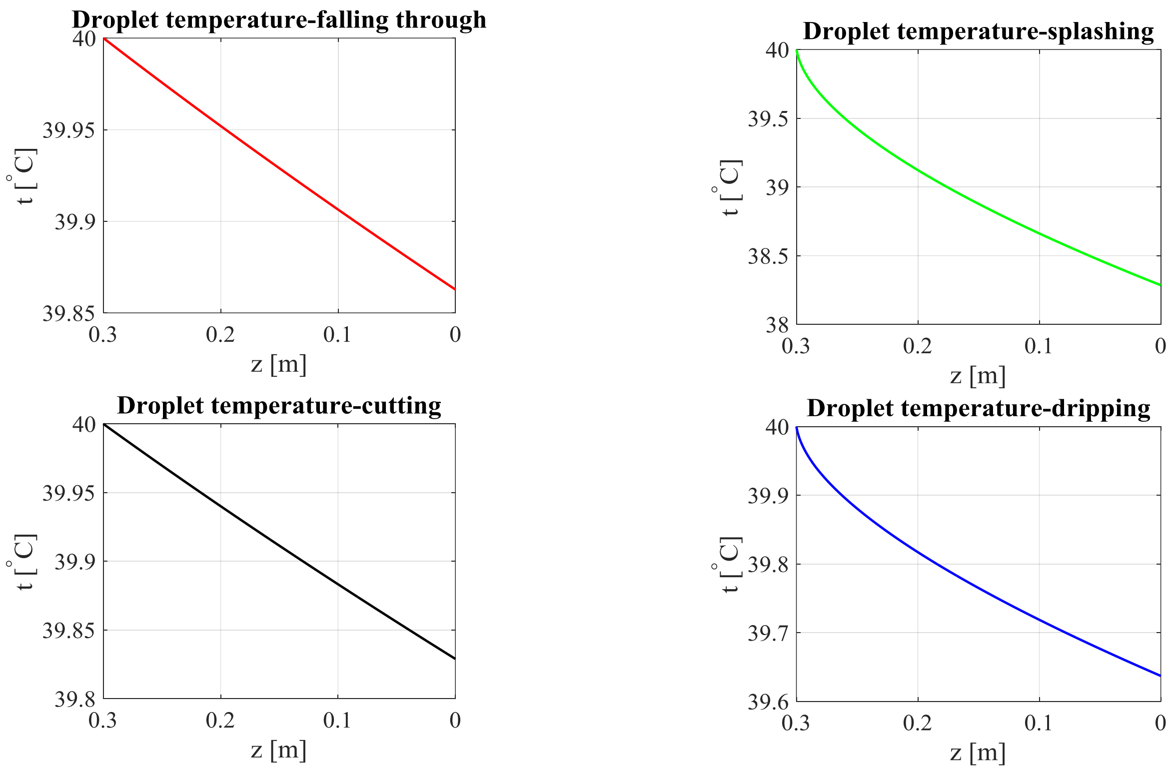

Figure 4.2 Droplet temperature decrease

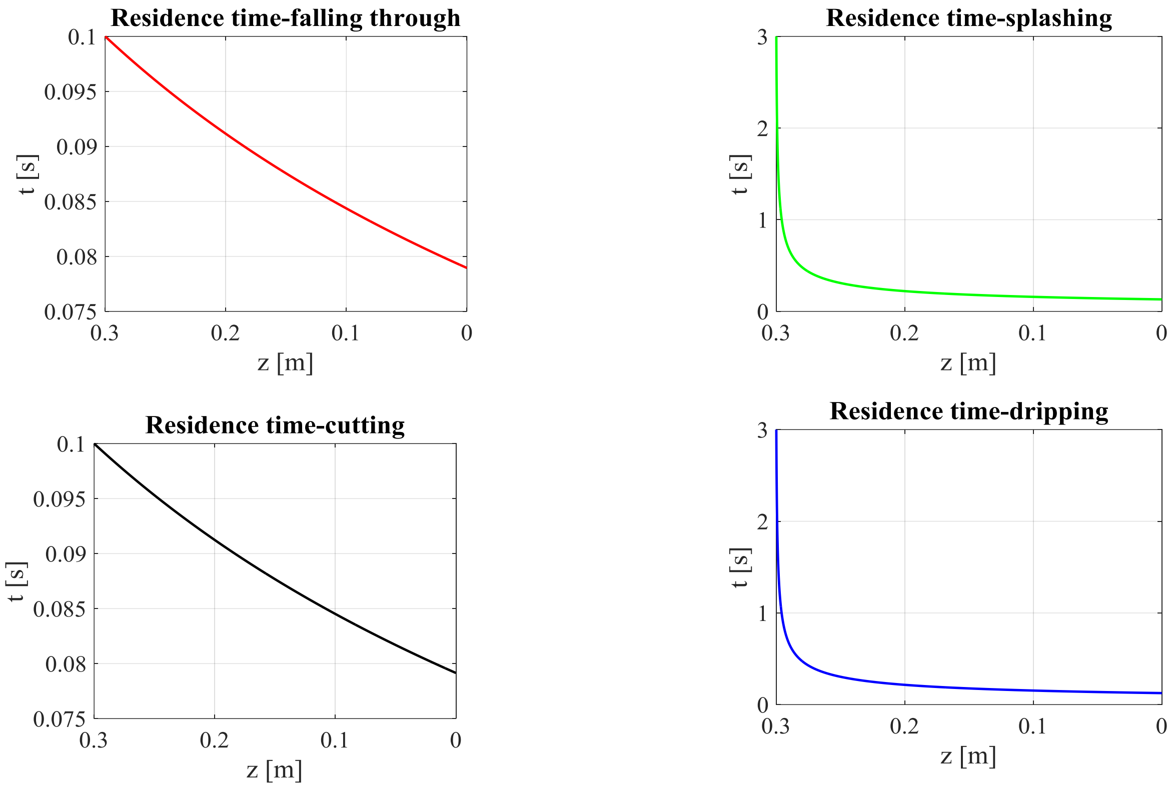

Figure 4.3 Residence time of droplets

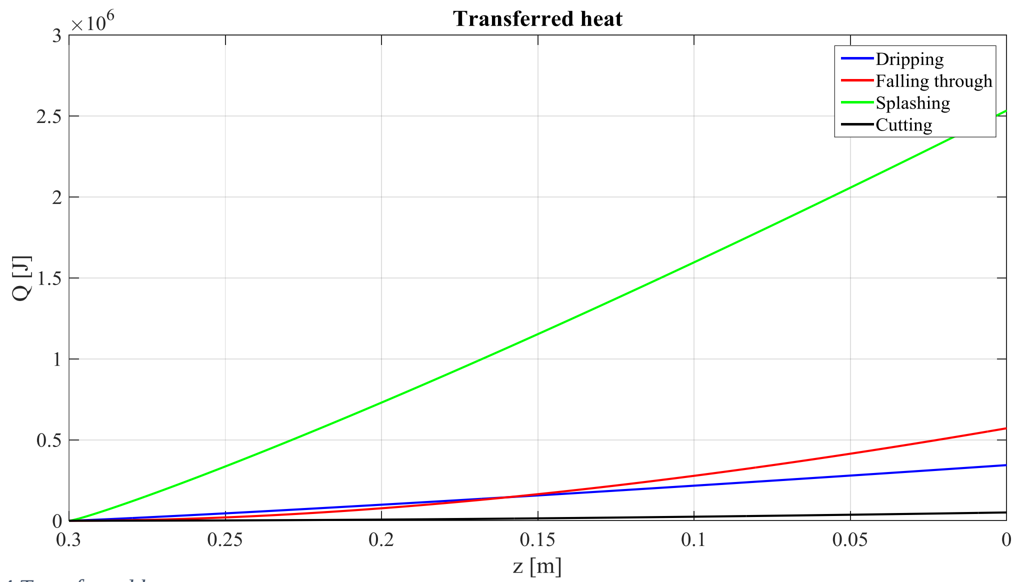

Figure 4.4 Transferred heat

5 CONCLUSION

Splashing and cutting are two main mechanisms of reducing water droplet diameters. Further research on droplet diameters created by splashing shall be taken as well as conditions under which droplets do not further reduce and become part of the water film on a slat. Dripping is a mechanism that creates a new spectrum of droplets from the water film on slat. A further investigation on shape of the slat influencing the dripped droplet diameter shall take place as well as the effect of Rayleigh instability.

The conclusion made by [40] about limit of air velocity 5 m/s shall be verified as the data seem to be insufficient. The use of slats to reduce diameter could be taken in advantage as well.

Author expects the droplet distribution to happen by this way: Droplet of a diameter created by nozzles fall down through the tower. When they hit the slats/bars of splash fills, the diameter-reducing mechanisms take place. These smaller droplets provide bigger area of cooling. However, as they fall down to next splash layer, they might eventually become part of the water film, as their size can't be no further reduced. Eventually the dripping mechanism takes place and creates a new spectrum of droplets. If the droplets don't join together with water film, their size might be reduced to the point when they are eventually driven out of the cooling tower.

To improve presented model stated in Chapter 4, the exact division between all used droplet creation mechanisms should be investigated and model should be modified with a new division for the next layers with new initial conditions calculated from the bottom of previous layer, that could lead to a possibility of modeling a whole cooling tower.

In general, future measurement should investigate if this is the correct description of splash/grid fills system and find the wanted ratio between droplet diameter and maximal possible cooling effect.

An introduction about cooling towers with a focus on characterization and inner structure was provided in Chapter 1. Inner structure of a cooling tower along with physical description of principle of evaporative cooling is provided in Chapter 2. Mechanisms of droplet creation are stated in Chapter 3 along together with proper sourcing and measurement provided by other authors description, describing mass and heat transfer in cooling towers with splash/grid fills. Chapter 4 contains a basic model that is ready to be used after editing starting conditions. Chapter 5 summarizes additional research that should be taken in future.

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