Estudio del refrigerante R134a en estado bifásico circulando en un tubo horizontal

Trabajo Fin de Grado

Oscar Blanco Fernandez
Julio de 2016
PROJECT WORK

for

Stud.techn. Oscar Blanco Fernandez
Spring 2016

Study of boiling of R134a in a horizontal small diameter tube
Studie av kokking av R134 på horisontalt rør med liten diameter

Background and objective

Flow boiling in small hydraulic diameter channels is becoming increasingly important in diverse applications such as refrigeration, power and process engineering. The need for high heat flux removal has been triggered by the development of new technologies ranging from computers, data centers, medical applications, electric cars, radars, satellite, lasers, to mention some applications. A fundamental understanding of the underlying physical mechanisms controlling these processes is a key element for the design of more efficient equipment.

During this project, the student will have the opportunity of operating a state of the art experimental facility for investigating flow boiling in a horizontal heated tube. The goal in this work will be to perform measurements of heat transfer and pressure drop during flow boiling under selected conditions. Correlate experimental data. Perform high-speed visualization and analysis of the flow.

Objectives during the project work

1. Literature review on heat transfer coefficient on horizontal flow boiling tubes
2. Preparation of the experiment, data acquisition, error analysis, and data processing
3. Analysis of the data

The project work shall comprise 15 credits.

A progress plan (Planned activities and scheduled progress) shall be submitted to the responsible subject teacher/supervisors for comments within 14 days after the candidate has received the project description.

The work shall be edited as a scientific report, including a table of contents, a summary in Norwegian, conclusion, an index of literature etc. When writing the report, the candidate must emphasise a clearly arranged and well-written text. To facilitate the reading of the report, it is important that references for corresponding text, tables and figures are clearly stated both places.
By the evaluation of the work the following will be greatly emphasised: The results should be thoroughly treated, presented in clearly arranged tables and/or graphics and discussed in detail.

The candidate is responsible for keeping contact with the subject teacher and teaching supervisors.

According to "Utøvende regler til studieforskriften for teknologistudiet/sivilingeniørstudiet ved NTNU" § 20, the Department of Energy and Process Engineering reserves all rights to use the results and data for lectures, research and future publications.

The report must be submitted to the Department in 3 complete, bound copies. Further, a separate page must be submitted, giving a short summary of the work and stating the author’s name and title of the project work. This information will be used in case of the work being referred to in journals, and must not exceed one typed page with double spacing. Additional copies should be given directly to the supervisor(s) involved in the project according to agreement with the supervisor(s). A CD with a complete copy of the main report in Word-format or similar, shall be submitted to both the subject teacher and the Department of Energy and Process Engineering.

The main report from the project work shall be submitted to the Department of Energy and Process Engineering within 24th July 2016.


Olav Bolland
Department Head

Principal Supervisor: Carlos A. Dorao

Carlos A. Dorao
Supervisor
Abstract

High heat transfer rates at reasonably low temperature differences can be obtained by utilizing a boiling fluid. However, the behaviour of the heat transfer coefficient becomes much more intricate, revealing the modelling of this behaviour quite complex. Nevertheless, a good model of this two-phase flow allows for an optimal design and, thus, a safer system with a higher efficiency regarding heat transfer.

An extensive research has been conducted in the past decades on this topic, however, many aspects remain unexplored. The literature survey presented in this work condenses previous results in a chronological order, gradually showing new discoveries and corrections on previous models. Yielding, in the end, a wide review of the state of the art on boiling R134a inside an horizontal, small diameter tube.

The purpose of this study is to perform an experimental investigation on an unexplored region, obtaining new results that may contribute for the elaboration of a more accurate model. For this end, a deep study was performed on the different aspects exhibited on the experimental results together with a comparison with the literature survey, allowing for the extrapolation of new conclusions on the topic.

Experiments were conducted inside a 5mm internal diameter tube with a pressure of 5.5 bar, mass fluxes ranging from $200\text{ kg/m}^2\text{s}$ to $400\text{ kg/m}^2\text{s}$ and heat fluxes ranging from $15.8\text{ kW/m}^2$ to $47.8\text{ kW/m}^2$. Under these conditions, due to the high heat flux and pressure selected, the nucleate boiling contribution on the heat transfer was found significantly stronger than the convective contribution. As a result, the heat transfer coefficient presented a strong dependence on the heat flux, while the effect of mass flux was only important for higher vapour qualities, were the convective heat transfer mechanism gains strength.

Deep focus was also made on the dryout region, revealing interesting behaviours regarding both the vapour quality at which dryout occurred and the HTC achieved at dryout inception. Moreover, a sharp increase of the heat transfer coefficient was found before dryout inception, this feature had been reported only once prior to this project and the experimental results presented in this work have revealed resourceful for the investigation of this new characteristic.
Acknowledgements

Thanks to the erasmus program that has allowed me to elaborate this project at NTNU, my family that has helped to make it possible, the new friendships acquired that have become my best support along the year, and my coordinator, Carlos A. Dorao, that has been always helpful.
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List of Abbreviations

HTC  Heat Transfer Coefficient
HCFC  Hydro Chloro Fluoro Carbon
HFC  Hydro Fluoro Carbon
GWP  Global Warming Potential
DWO  Density Wave Oscillations
Chapter 1

Introduction

The use of energy in the world has increased in the last century in over an 800%. Energy dependency is present everywhere, from domestic to industrial environments its increasing demand urges for a more efficient usage. Amongst the activities in which this energy is used, heat transfer covers a significant part as it represents a vital feature of almost any energy converting system. For this purpose, enhancing the heat transfer is crucial in order to reduce the thermodynamical losses. Thus, improving the heat transfer coefficient of a heat exchange process is of vital importance in order to reduce the amount of energy needed for the system.

In the pursuit for a larger heat transfer coefficient, heat exchangers designed to be used with a boiling fluid have proven to yield larger heat transfer coefficients. On the downside, the modelling of the heat transfer in a two-phase fluid represents a great challenge due to the complexity of the boiling process. Moreover, designing a heat exchange system relying on an unrealistic model, will likely result in energy losses due to an inefficient heat exchange, and in worst cases, it may even lead to burnout crisis that often produce a physical damage in the facility.

Thus, it can be noticed the importance of providing realistic models in which the industry can rely when designing heat exchangers. This aim towards accuracy urges researches to be conducted for each specific arrangement in which the exchanger may be disposed, distinguishing as well for the type of refrigerant used.

This project was focused particularly on the study of refrigerant R134a along horizontal smooth tubes. This setting is of significant relevance due to its wide use in the industry. Furthermore, experimental researches on flow boiling in horizontal smooth tubes have been conducted for almost a century, but only when finding an alternative for HCFCs started becoming an issue (due to their high chlorine concentration) was R134a studied in these experiments.

The modelling for R134a has revealed challenging and the correlations achieved still fail to predict many aspects of its behaviour. When compared to the experimental database, the errors are found mainly in the high quality region, where transitions between annular, dryout and mist flow regimes greatly increase the complexity of the process.

For this end, the research conducted in this project is focused on this region and aims to provide guidance towards a better modelling by providing new
experimental data and reviewing the different studies developed on the topic for further comparison.
Chapter 2

Literature Survey

2.1 Initial approach to heat transfer in tubes

Convective heat transfer is one of the main heat transfer mechanism and usually the dominant form of heat transfer in liquids and gases. It involves the combined processes of conduction (heat diffusion) and advection (heat transfer by bulk fluid flow). The effect is therefore based on the transference of heat due to fluid movement, thus, enhancing this movement enhances convection. For the case of a fluid flowing through a tube, convection will be stronger if mass flux is increased. For this case, convection is often distinguished as the dominant heat transfer mechanism when the HTC is almost independent on heat flux but strongly dependent on mass flux and vapour quality.

Nucleate boiling heat transfer occurs when the temperature of the surface containing the fluid increases over the saturation temperature. At this point isolated bubbles form at different nucleation sites and separate from the surface. This separation induces considerable fluid mixing near the surface and substantially increases the convective heat transfer coefficient. Concerning the case of a boiling fluid through a tube, nucleate boiling is distinguished as the dominant heat transfer mechanism when the HTC is nearly independent on vapour quality and mass flux but strongly dependent on heat flux.

Annular flow is a flow regime encountered in boiling fluid through tubes. It is characterized by the presence of a liquid film flowing on the channel wall (in a round channel this film is annulus-shaped which gives the name to this type of flow) and with the gas flowing in the gas core. The flow core can contain entrained liquid droplets. In horizontal channels the film thickness is non-uniform around the channel perimeter due to gravity. Indeed, the layer thickness presents gradually reduced from the bottom to the top of the tube.

Mist flow is the flow regime encountered at the highest vapour qualities for flow boiling in tubes. At this stage the tube only contains vapour with entrained droplets of liquid which will continue evaporating until only vapour is left in the tube. Due to the low conductivity of the vapour the heat transfer coefficient is greatly reduced.
**Dryout** represents the transition from annular flow to mist flow. During dryout the liquid film next to the wall evaporates until the layer disappears and only vapour and droplets of liquid are left.

### 2.2 State of the art on HTC for boiling R134a over high quality values

The first attempt to model the annular to mist flow transition during evaporation in horizontal tubes was made by Lavin and Young (Lavin and H. Young, 1965). They proposed that the transition between annular and mist flow covered another region corresponding to the burnout or dry wall condition which, until then, had been considered to occur at a certain point and not gradually. Their experiments were carried for refrigerants R-22 and R-12 and with the used apparatus heat transfer coefficient could not be obtained within the dryout regime nor could be studied the conditions under which the dryout regime ends and stable mist flow was established. However, their work prompted the study of the dryout region in horizontal tubes.

Three decades later Kattan, Thome, and Favrat, 1998a would form the first generalized heat transfer pattern map were refrigerant R-134a (which at the moment was a new refrigerant) was used for the experimental database. In comparison with the earlier version in which the model was based (Steiner, 1993), Kattan, Thome, and Favrat, 1998a modified the mist to annular flow boundary making it more realistic and incorporating the effect of the onset of dryout at high vapour quality. Another keypoint of their study was that the map was also transformed into a mass velocity versus vapor quality format, which is much more useful when identifying the flow patterns.

Heat transfer coefficients with R-134a achieving over vapor qualities were shown in a second part of this publication (Kattan, Thome, and Favrat, 1998b) for a saturation temperature of 3.9°C, internal diameter of 10.92mm and different mass fluxes and heat fluxes as can be seen in figure 2.1. To the author’s knowledge these are the first experiments in the literature showing the HTC for the dryout transition with R-134a.

Kattan, Thome, and Favrat, 1998b also made special emphasis on the fact that in the experiments the refrigerants inside the tubes were heated by hot water flowing counter currently in the annulus instead of using electric heating and thus, corresponding more to the real situation in a water chiller evaporator. This is of relevance as most test facilities have used electrical heating and, according to Kattan, Thome, and Favrat, 1998b, using an electrically heated tube the heat flux is kept artificially constant before and after the onset of dryout. Therefore the heat flux becomes an independent variable imposed by the experimenter. This means that in an annular flow with partial dryout the heat transfer coefficient at the top of the tube decreases while the electrical resistance tends to keep a constant heat flux, inducing a temperature increase on the tube wall.
2.2. State of the art on HTC for boiling R134a over high quality values

The models published in these articles would be later corrected by Wotjan2005; Wotjan2005a whose flow-pattern map and heat transfer models are the basis for today’s corrections.

Although R-134a was not used in this research, it’s repercussion is of critical importance for this project’s literature review. On their efforts towards studying the transition from annular to mist flow they integrated a new boundary in the flow pattern map that covered the dryout region, thus, dividing the traditional annular to mist flow transition in annular-dryout and dryout-mist.

It was now obvious with the observations made in their experiments that there was no step-wise transition from annular flow to mist flow. For this new regime they sketched the dryout region as depicted in figure 2.2. It can be seen here how dryout occurs at the top of the tube first, where the liquid is thinner, and then progresses downward around the perimeter until reaching the bottom.

Another significant observation regarding dryout was reported in their experiments stating that the qualities at which dryout inception and completion occur increase with mass velocity. Should be reminded that these experiments were not using R-134a as a refrigerant so their results are not conclusive to our study. However, they shall be given attention as they indicate how other refrigerants may behave.

Also a matter of interest reported in Wotjan2005 was the observation of hysteresis in the process when reducing the heat duty after reaching mist flow. This points to a possible error when testing for increasing power of the preheaters instead of decreasing their power after having reached the desired quality.

On this same year Saitoh, Daiguji, and Hihara, 2005 reported experiments for different small diameters with refrigerant R-134a. Results showed that as the tube diameter decreased: (i) contribution of forced convective evaporation to boiling heat transfer decreased; (ii) onset of dryout occurred in a lower quality region.
Despite the fact that, as can be observed in table 2.1, these experiments were most of them performed with diameters too small for the range focused in this project ($D > 3$mm). Yet, Saitoh, Daiguji, and Hihara, 2007 stated that these two conclusions could be applied to higher diameters. Furthermore, the article uses these results to elaborate a new correlation for heat transfer which is said to be appropriate for internal diameters ranging from 0.5mm to 10mm.

As HCFCs were phasing out due to their large concentration of chlorine, harmful for the ozone layer, investigations on HFCs such as R134a became more important as this new family was regarded as a likely substitute for HCFCs. For this purpose Greco, 2008 compared experimentally different HCFCs and HFCs (including R-134a). Several conclusions affecting the heat transfer for high vapour qualities were drawn from the experiments: (i) HTCs always increase with mass flux following an exponential relation; (ii) HTCs depend on heat flux only in the region where nucleate boiling dominates; (iii) HTCs increase with saturation temperature due to the nucleate boiling contribution, this increase is less noticeable for higher vapour qualities.

Comparison between the different refrigerants also presented R-134a as a better option, with a higher HTC than the rest. In addition, this difference was observed to increase with the saturation temperature. Favourable researches towards R-134a such as this one induced an special interest on the refrigerant and consequently urged for further investigations during the next years.

da Silva Lima, Quibén, and Thome, 2009 was (to the author’s knowledge) the first report to show HTC for R-134a with small quality increments in the high quality region. In this deep study into R-134a, different heat fluxes, mass velocities and saturation temperatures were used as variables (table 2.1). The experimental procedure used, in which only one of the variables would change while the other two remained constant, allowed for an orderly classification of the effect of each of the variables in the HTC, which
for higher vapour qualities showed the conclusions reported in the following paragraphs. Figure 2.3 shows the experimental results in which those conclusions are based and aims to provide the reader with a visual reference that allows for a better understanding of the written results:

Saturation temperature influence: Opposite to Greco, 2008 the HTC does not always increase with $T_{\text{sat}}$ instead, for higher vapour qualities the experiments show higher HTCs with lower $T_{\text{sat}}$. It is explained that this decrease of HTC with $T_{\text{sat}}$ for higher vapour qualities is due to: (i) Vapour density increases with $T_{\text{sat}}$, thus its velocity decreases and thereby its convective boiling contribution; (ii) Liquid thermal conductivity decreases with $T_{\text{sat}}$. The same reasons are said to force the HTC at dryout inception and completion to decrease with $T_{\text{sat}}$ while the vapour quality at which they occur is clearly seen to increase. During the dryout region, the curves with different $T_{\text{sat}}$ merge together again and intersect.

Mass velocity influence: Its influence on the HTC is more important for higher vapour qualities and always leads to an increase in the HTC as it was also reported by Greco, 2008. Mass velocity is also said to decrease the vapour quality at which dryout inception and completion occur due to the increase that mass velocity produces on the convective boiling contribution.

Heat flux influence: The vapour quality at which dryout inception occurs is observed to decrease with increasing heat flux. This earlier dryout implicates that the HTC achieved at dryout is lower for higher heat fluxes. Thus stating that an increasing heat flux decreases the HTC of the onset of dryout.

Kim and Mudawar, 2013 focused on the study of dryout and claimed that dryout is closely associated with the saturated inlet conditions and the development of a clearly identifiable annular flow regime. The article differentiates dryout depending on the type of heat transfer regime were they occur: (i)For nucleate boiling dominant heat transfer bubbly and slug flow regimes occupy a significant portion of the channel length and the heat transfer coefficient decreases with vapour quality due to gradual suppression of nucleate boiling; (ii)On the other hand for convective boiling dominant heat transfer, annular flow spans a significant fraction of the channel length. Here, gradual evaporation and thinning of the annular liquid film causes the heat transfer coefficient to increase along the channel length.

With a sufficiently high wall heat flux or sufficiently long channel, the annular film becomes vanishingly thin for both heat transfer regimes and a lack of perfect symmetry in the film flow or uneven evaporation causes initial dry patches to form at the location of dryout incipience where the HTC begins to decrease appreciably until dryout completion occurs. Schematics of the flow regimes with either nucleate boiling heat transfer or convective boiling heat transfer as dominant taken from this article are shown in figure 2.4.

Grauso et al., 2013 compared R1234ze(E) (a low-GWP refrigerant) with R134a. For this comparison further experiments were made with R134a covering part of the high quality region. Despite only some of the experiments were
conducted until dryout completion, their results are quite interesting since they help corroborate most of the conclusions affirmed by da Silva Lima, Quibén, and Thome, 2009 while being conducted with a much smaller diameter as can be seen in table 2.1.

Another important observation can be made when comparing the experimental database shown in Grauso et al., 2013 that is displayed in figure 2.5 with the one in da Silva Lima, Quibén, and Thome, 2009 displayed in 2.3 (c) under similar conditions but with a much larger diameter (13.84mm): Recalling the mentioned article of Saitoh, Daiguji, and Hihara, 2005, whose results showed that a decrease in the internal diameter leads to a lower vapour quality for the dryout inception, we can observe the exact opposite behaviour in this comparison as figure 2.5 shows a vapour quality for the dryout inception higher than 0.95 while in figure 2.3 (c) the different curves present the dryout inception at a similar vapour quality of around 0.85. This contradiction in the literature shall be reminded as it will be commented later on the discussion part of this report.

The next set of experimental results on the topic would be published in Chiapero, Fernandino, and Dorao, 2014 where a different region was explored by setting a larger saturation temperature in the experiments conducted (table 2.1). The results show a much larger nucleate boiling contribution.
2.2. State of the art on HTC for boiling R134a over high quality values

As expected (nucleate boiling was found to increase with $T_{\text{sat}}$ in previous articles). For instance, in the experiments with the highest heat flux and lowest mass flux, HTC shows almost no dependence on the vapour quality, revealing that nucleate boiling is the most important mechanism.

Regarding dryout inception under the conditions used of high saturation temperature and with an internal diameter of 5mm, the experiments with different mass fluxes and heat fluxes shown in this article all present a vapour quality for the dryout inception of at least 0.92. The vapour quality at which dryout completion occurs is slightly over 1, thus showing an abrupt fall of the HTC in the dryout region.

Simultaneously on the same year, Kundu, Kumar, and Gupta, 2014 published experimental results for R134a using an internal diameter of 7mm and low saturation temperatures (table 2.1). These results show an unexpected behaviour quite different from what has been seen in other articles. Dryout inception occurs at a significantly low vapour quality of 0.7, but more surprising is that the experiments cover until a quality of 0.85-0.9 and for these qualities dryout completion is not presented, thus showing a remarkably large dryout region that covers qualities from 0.7 to at least 0.85. Those results shall be subject of further inspection in the discussion part of this report.

On a different aspect of HTC for a boiling fluid through a tube, Pike-Wilson and Karayiannis, 2014 made a study on the influence that the material used in the heated section has on the experimental data acquired. He compared the results with stainless steel, brass and copper tubes. The study reports that the magnitude of the HTC is similar for all three materials but with a slight variation in trend. The heat transfer coefficient is seen to peak at high
vapour qualities for stainless steel and brass, which is less evident with copper.

This conclusion has an important relevance for the evaluation of the results collected in this literature review. The different experiments that have been mentioned do not use the same materials so it is important to consider the effect that this might have had in the results yielded by each of them. While Grauso et al., 2013; Chiapero, Fernandino, and Dorao, 2014; and Deng, Fernandino, and Dorao, 2016 (which will be mentioned next) conducted experiments with stainless steel, Kattan, Thome, and Favrat, 1998a; and da Silva Lima, Quibén, and Thome, 2009 used copper tubes.

The most recent set of experimental data in this literature review was acquired by Deng, Fernandino, and Dorao, 2016 that made specific focus on higher vapour qualities. Experiments reported data between qualities of 0.7 and 1.2 with the smallest quality increments that have been observed in the articles mentioned in this literature review, thus allowing for a detailed description of the behaviour of the HTC as can be seen in figure 2.6.

This study includes various novelties both in the experimental procedure and in the results. Regarding the experimental procedure: (i) A heating down approach from qualities around 1.2 was conducted instead of heating up from the lowest quality. A possible error due to the "heating up" procedure was already mentioned in Kattan, Thome, and Favrat, 1998b. Moreover, in this article, one experiment with "heating up" was added in order to show the improvements that the "heating down" procedure implies. The results can be appreciated in figure 2.7 showing that there is a noticeable hysteresis effect in the "heating up" procedure; (ii) Instead of maintaining a constant heat flux in the testing heater, the power in all the heaters was equally decreased to lower the quality. It is said in the article that this procedure avoids the jump in the wall temperature that is observed when the
onset of nucleate boiling occurs or sudden changes in the flow regime.

The novelty regarding the shape of these curves is the appearance of a sharp increase of the HTC before the dryout inception. This article is the first one to report such behaviour and affirms that the reason behind it is a slight decrease in the wall temperature. For better illustration the differences between the inner wall and saturation temperature ($\Delta T = T_w - T_{sat}$) was plotted in the article and can be observed in figure 2.8. Deng mentions that the possible reasons may be that "at high qualities, the vapour velocity is quite high and the film is very unstable until dryout occurs. Meanwhile, the interfacial shear between the vapour and the film enhances the heat transfer. On the other hand, the vapour of high velocity and the high wall heat flux may contribute to the entrainment, which will reduce the film thickness and the heat transfer coefficient will increase".

The last articles mentioned make the state of the art on heat transfer for R134a in horizontal smooth tubes over high vapour qualities. Thus, the correlations elaborated in these articles make up for the current different models that allow to extrapolate the experimental database to a much larger range of conditions. Clearly, these models differ from each other depending mostly on the experimental database used to develop the correlations. Thus, it is of importance to have present the differences between all the experiments that have been conducted on the topic. Table 2.1 shows the experiments in the area of interest of this project, all of which correspond to articles reviewed in this literature survey.
**Figure 2.7:** Heating up and heating down procedures comparison by Deng, Fernandino, and Dorao, 2016

**Figure 2.8:** Difference between the inner wall and saturation temperatures as plotted in Deng, Fernandino, and Dorao, 2016
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<th>Mass Flux ([Kg/m^2s])</th>
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<td>150 - 450</td>
<td>5 - 15</td>
<td>0.9 (D=3.1mm)</td>
<td>1 (D=3.1mm)</td>
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<td>da Silva Lima, Quibén, and Thome, 2009</td>
<td>13.84</td>
<td>7.5; 17.5</td>
<td>300; 500</td>
<td>5; 15; 20</td>
<td>0.8 - 0.9</td>
<td>0.86 - 0.91</td>
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</tr>
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<td>Grauso et al., 2013</td>
<td>6</td>
<td>5 - 20.4</td>
<td>146 - 520</td>
<td>-2.9 - 12.1</td>
<td>0.1 - 0.9/1</td>
<td>0.96</td>
<td>0.99</td>
</tr>
<tr>
<td>Chiapero, Fernandezino, and Dorao, 2014</td>
<td>5</td>
<td>10.5; 20</td>
<td>297.7 - 497.8</td>
<td>33.4 - 34.3</td>
<td>0 - 1</td>
<td>0.9</td>
<td>1</td>
</tr>
<tr>
<td>Kundu, Kumar, and Gupta, 2014</td>
<td>7</td>
<td>3 - 10</td>
<td>100 - 400</td>
<td>5.8 - 8.9</td>
<td>0.1 - 0.9</td>
<td>0.7</td>
<td>&gt;0.9</td>
</tr>
<tr>
<td>Deng, Fernandezino, and Dorao, 2016</td>
<td>5</td>
<td>varying</td>
<td>300 - 400</td>
<td>15.7 - 39.4</td>
<td>0.01 - 1.2</td>
<td>0.82 - 0.89</td>
<td>1</td>
</tr>
</tbody>
</table>

**Table 2.1:** Experimental database on heat transfer for R134a in horizontal smooth tubes over high vapour qualities
Chapter 3

Experimental facility

This chapter aims to present the different aspects of the experimental facility used by providing a detailed description of its current set-up and instrumentation. The construction of this facility has been possible thanks to the great effort conducted by both academic and technical staff prior to the work presented on this project.

The rig has a vast amount of settings that allow for reproducing different processes regarding flow in horizontal circular tubes. In this chapter only the features corresponding to the arrangement that was used for the experiments presented in this work will be covered.

3.1 Description of apparatus

3.1.1 Thermo-hydraulic system

The experimental facility is an R134a closed loop consisting of a main tank, a pump, pre-conditioner, a heated test section with in and outlet restrictions, and a condenser. In addition, a visualization glass is incorporated after the test section which, by using a high speed camera, allows for flow visualization and recording. A coriolis flow meter is used before the heated test section in order to give an accurate measurement of the mass flux circulating. The loop with these mentioned features is represented in figure 3.1.

3.1.2 Working fluid

R134a, also known as Tetrafluoroethane (CF3CH2F), from the family of HFC refrigerants is used as a working fluid in this facility.

R134a first appeared in the early 1990s as a replacement for Dichlorodifluoromethane (R-12), which has significant ozone depleting properties. R134a has been atmospherically modelled for its impact on depleting ozone and as a contributor to global warming. Due to its high GWP it is now being substituted in several environments, such as the automotive industry, for lower GWP refrigerants. However, its relevance and use in the industry is still high.
It has great thermodynamic properties for its use as a refrigerant, low temperature of vaporization and a relatively high heat of vaporization. At the same time it is safe for normal handling as it is non-toxic, non-flammable and non-corrosive. Therefore proving safe for its use in an experimental facility.

3.1.3 Pump

A gear pump (GB-MICROPUMP) with magnetic drive coupling is used to circulate the fluid through the circuit. The liquid refrigerant enters the pump from the bottom of the main tank, thus, assuring that the level of the tank would have to be at its lowest in order to malfunction. Nevertheless, checking the main tank’s liquid level can be easily done by looking into two sight glasses in the vessel.

The speed of the pump can be regulated by changing the DC-voltage provided to the motor drive. This function can be regulated through the software interface in order to dictate the flow rate required in the loop for a certain experiment. In addition, a bypass valve parallel to the pump allows for a wider range of experimental flow rates.

3.1.4 Pre-conditioner

The temperature of R134a entering the test section is controlled by a plate-and-fin heat exchanger (B8THx14 SWEP). Here, heat is exchanged with a water-glycol mixture which is subsequently cooled by an Applied Thermal Control (ATC) K9 chiller. Controlling the inlet temperature of the R134a
3.1. Description of apparatus

into the test section is therefore achieved by controlling the temperature of the chiller.

The chiller’s temperature is set as one of the inputs in the software interface. With regard to the maintenance of this system it is important to always assure a sufficient level of glycol in the chiller.

As for the function that this chiller has in the experimental procedure, regulating the inlet temperature to the test section implies setting the subcooling with which the fluid enters the tube. This subcooling will be one of the factors that dictate the quality at which the fluid is encountered at a given distance in the tube.

3.1.5 Heated test section

The test section is a 2035 mm long, horizontal circular tube made of stainless steel. Its internal diameter is 5mm and the outside diameter is 8mm. The entire test section is equipped with an electrical heating system that works by application of a rectified sine wave (Joule heating).

Six electrodes are disposed limiting 5 equally long segments along the tube. This disposition allows the reproduction of non-uniform heating by individually varying the electrical power supplied to each segment. For this purpose, the software interface allows for an independent control of each segment.

Insulation over the test section reduces the heat loss to the surroundings which will never exceed 8% and is indeed accounted for when calculating the actual heat transfer to the fluid.

Testing in the tube is done through various measuring instruments. Seven pressure taps are located in the tube for differential pressure drop measurements. Pressure transducers connected to the pressure taps allow for a custom point of measurement and the overall test section pressure drop. External thermocouples measuring the wall temperature together with two internal thermocouples are able to yield the heat transfer supplied to the fluid. Ten thermocouples are distributed along the outside bottom wall of the test section while there are seven on top. An schematic view of the disposal of the mentioned features of the heated test section can be found in figure 3.2.

Figure 3.3 presents the test section viewed from its exit. Pressure taps are connected from the left hand side and internal and external thermocouples from right. Electric power is applied through the copper blocks. The test section is mounted between two sheets of insulating material, as the one shown in the picture, to minimize heat loss to the surroundings.

3.1.6 Flow restrictions

As was observed in figure 3.1, the test section is equipped with an inlet throttling valve and an exit orifice.
Chapter 3. Experimental facility

The inlet valve can be manually operated in order to change the conditions of the flux. Bad regulation of the valve may lead to density wave oscillations. This phenomena is well explained in Sorrum, 2014. At the same time, closing the valve up to a safe limit when starting the facility increases the flow speed and helps avoiding vapour entering the test section.

3.1.7 Condenser

Working fluid leaving the heated section is condensed back to liquid form in the tubes of a shell and tube heat exchanger (CFC-12-Alfa Laval). The excess of heat is exchanged with the water-glycol found in the shell-side.

This secondary coolant circuit is thermally controlled by an ATC K6 Chiller. Same as with the K6 chiller mentioned earlier, the temperature of this chiller can be adjusted through the software interface. This temperature will dictate the loop’s pressure and, thus, the saturation temperature at which R134a boils.

3.2 Associated instrumentation

The next section will describe the measurements and the accuracy of different instruments present in the facility and relevant to this study.

3.2.1 Mass flow rate

Mass flow rate is measured before the fluid enters the test section. The reason behind it is that accurate measurements on mass flow for a two-phase flow (which would be encountered at the exit) are generally harder.
In order to record the flow rate, two Coriolis flow meters (Bronkhorst Cori-Tech R134A 3L/min) are placed upstream of the test section. The first one (G1) is situated close to the pre-conditioner while the second one is placed right upstream of the test section. An accuracy of 0.2% of the reading is given by the supplier.

The volumetric flow rate that is read by the Coriolis flow meter is converted into mass flux by using the densities stated in NIST REFPROP properties database.

### 3.2.2 Pressure

System pressure is calculated as the absolute pressure recorded between the inlet restriction and the heated test section. The overall accuracy for the GE-UNIK 5000 Premium pressure sensor is 0.04% of full scale where full scale is 16 bar. This translates to about 0.11% (or 0.01 bar) in the relevant experimental pressure range.

### 3.2.3 Temperature

The fluid temperature was recorded at the inlet of the heated section. All thermocouples used in the facility are standard K-Type of 0.5 mm diameter. The thermocouple accuracy after in-house calibration was found to be 0.1 K.

In order to calculate the inlet subcooling (difference between the saturation temperature and fluid temperature) the measured inlet temperature was compared to the saturation temperature corresponding to the absolute pressure. Calculations for obtaining the saturation temperature from
the absolute pressure were done using the equilibrium thermodynamical properties presented in NIST REFPROP.

3.2.4 Heat Flux

The power supply is constructed in-house. A voltage potential from a controller-rectifier circuit is applied over 6 electrodes evenly distribute along the heated section. Though smooth direct current (DC) would have been the ideal, the use of capacitors in the power supply has been omitted to reduce load on the transformers, resulting in a rectified sine wave. Due to the massive ripple in the signal, a digital oscilloscope was used to obtain the actual shape of the voltage and current signal to each of the heated sections. Data is acquired at every 0.1 second (10Hz) while the mains frequency is 50Hz rendering the first unusable to sample the later. Thus, averaged DC-equivalent values derived by numerical integration of the actual signal shape must be used as correction factors to the voltage and current measured by the acquisition card.

Errors in the heat input are also associated to the voltage and current measurements. Calibration of the measurements has shown <10% error. Accuracy of the power measure chain was taken assuming a power of 200W giving a final accuracy of 20W (Ruspini, 2013).

Since the heated section is thermally insulated, most of the heat generated in the pipe wall is absorbed by the fluid. However, the effect of thermal losses must also be taken into account when determining the heat transfer to the fluid. Calibration of this heat transfer was done using the test section inlet and the two internal thermocouples in order to measure the heat transfer and compare it with the heat transfer yielded by considering energy conservation. It is remarked that the heat losses in experimental cases are never higher than 8%.

3.2.5 Uncertainties and accuracy of measurements

Details regarding the accuracy of the facility instrumentation as well as the uncertainties of the main operational parameters can be found in tables 3.1 and 3.2 respectively.

3.2.6 Software interface

The National Instruments LabVIEW software (short for Laboratory Virtual Instrument Engineering Workbench) is used to control and monitor the experimental facility. The software interface is used to set pump speed, control heaters and the two chillers (K6 and K9). It is also used for monitoring the conditions measured by the heaters, flow meters, absolute and differential pressure transducers, and thermocouples in a schematic flow diagram. Moreover, the software provides a very useful on-line visualization of the inlet flow trace. The main window of the LABVIEW software interface is presented in figure 3.4.
### 3.3 Main specification overview

Table 3.3 provides a summary of the main specifications of the facility used.

### 3.4 Risk assessment and safety

A complete risk assessment report of the facility was created by Ruspini and Langorgen, 2011 in order to get an operation authorization at the Thermal Laboratory at NTNU.
Amongst the main hazards that can be recognized in the experimental apparatus: (i) The loop contains a pressurized fluid even when not in operation. As a general precaution, safety glasses were always used when working close to the rig. (ii) The room has a sizeable volume so local frostbites is the primary risk in case of leakage.

The facility was controlled and monitored from a computer station next to it. Repetitive strain injuries (RSI) might have been a risk involved in this kind of laboratory work. However, none of the mentioned issues, or other incidents, were ever encountered.
Chapter 4

Methods

This chapter describes and explains the scientific methodology employed. The aim is to provide information on the experimental procedures that have been used in order to achieve the desired set of conditions, minimizing possible deviations from the real model. That is a throughout description on how to collect the necessary experimental data and the analytic procedures from which conclusions will be drawn. The intention is to bridge the previous chapter describing the experimental facility to the following focusing experimental results. The study shown in this chapter was previously conducted by Sorrum, 2014; Ruspini, 2013; Ugueto, 2013 and thus, their work has been taken as a reference.

4.1 Execution of experiments

The task is to determine the behaviour of the heat transfer coefficient in an horizontal in-tube boiling system. This has to be achieved by providing a reliable model that accurately replicates this case. Thus, an appropriate way of conducting experiments has to be developed.

4.1.1 General steps in operating the facility

Inlet restriction, outlet configuration and the pump bypass valve are configured.

The pump is started.

K6 and K9 chillers are set to values corresponding to the desired system pressure inlet subcooling.

Heat is applied close to the desired starting value (close to a quality value of 1.2)

Pump drive, condenser chiller (K6) and conditioner chiller (K9) require iterative tuning in order to achieve an accurate flow rate, pressure and subcooling according to the planned experiment. Adjusting one variable usually affects several parameters making this process quite complex.

Tuning of operating condition is manually carried out by the operator.
A considerable run-in time at the given conditions is needed to allow the system to settle at a true steady state. This can typically take an hour for each set of conditions.

Once set at the desired conditions, two experiments are measured maintaining the same inputs.

Power on the preheaters is decreased to a lower value in order to decrease the quality in the test section.

The system is allowed time to settle to this condition. Once it is set, two experiments are measured.

Power is again decreased in the preheaters repeating the same process continuously until achieving the lowest power on the preheaters.

Experiments are conducted for 150-200 seconds. Settling time in between experiments depends on the region that is being tested but generally takes over 180 seconds.

The second experiment conducted under each quality, is processed before it has finished in order to observe its resemblance to the first experiment. If the results of both experiments are too distant from each other, further experiments are conducted until an accurate result is achieved.

### 4.1.2 Stable system configuration

Measuring with the facility under the desired conditions has to be performed cautiously. Paying attention to possible deviations from the model to be replicated is crucial. On this frame, two incidents that must be avoided have been found likely to occur if the required measures are not taken:

**Appearance of DWO** specially at lower heat fluxes. Density Wave Oscillations appeared when the inlet valve was widely open. Thus, when conditioning the set up of the first experiments, inlet valve had to be only slightly opened in order to avoid DWO but still allowing for safe circulation of the refrigerant.

**Difference in mass flux measurements** was found between the two flow meters. This appeared when starting the pump as a consequence of accumulated vapour between both flow meters. In order to avoid this deviation, mass flux was abruptly increased, for a small period of time, by opening the inlet valve (manually) and increasing the mass velocity (through the computer station). As a result, vapour would move on to the heating section. Inlet valve and mass flux were slowly changed to their desired conditions after measurements from both flow meters showed similar enough values.
4.2 Data acquisition and logging

The fact that all experimental data is acquired and logged digitally, gives almost unlimited opportunities when it comes to data processing and plotting. “One experiment” is captured by logging in a 150-200 seconds time interval. Experiments are repeated at the given conditions until it is evident that it resembles the steady state nature of the system. Acquisition period (sampling interval) was set to 100 ms (i.e. 10 samples per second) during all experiments.

Several MatLab scripts have been prepared to do monitoring and processing of experimental data. Some more specific measurements required for different scripts to process the data and, as mentioned before, processing the data could be conducted while still running the experiment, allowing to follow the results.

4.3 Data reduction

The rig facilitates a two figured number of sensors in which data is logged continuously when experiments are running. It goes without saying that a significant effort has been spent in data reduction. That is to transform the bulk numerical information derived from in-experiment measurements into a corrected, ordered and simplified form. The prime goal is to convert experimental results into a suitable and convenient form that can be easily summarized in charts and tables.

Among these key figures characterizing the system is the heat transfer coefficient. This step is preformed after data from one experiment has been time averaged. Results that for different reasons are out of trend are left out, in particular if the reason is due to a known error or disturbance. This could for instance be sudden change in temperature inside laboratory or simply that insufficient time was spent for the condition to settle.

4.4 Measuring of the HTC

The heat transfer coefficient is the proportionality coefficient between the heat flux and the thermodynamic driving force for the heat flow ($\Delta T$). The heat transfer coefficient for convective boiling flows is based on the wall surface temperature ($T_s$) and bulk fluid temperature ($T_i$).

$$h = \frac{q^n}{T_s - T_i}$$

There are several ways to quote a heat transfer coefficients, one is the overall, or global, heat transfer coefficient. To give a wider perspective on boiling flow heat transfer, a local heat transfer coefficient will also be quoted on two locations were fluid temperatures could be attained directly from internal thermocouples.
It should be noticed that this work will name the global, or length averaged, heat transfer coefficient the overall heat transfer coefficient. This overall (global) heat transfer coefficient do only account for the heat transfer inner wall of the heated tube to the fluid.

### 4.5 Global HTC

Using an average of the difference between the surface and fluid temperatures along the length of the heated section and the total heat flux transferred to the fluid, the global heat transfer coefficient was calculated.

\[
\bar{h} = \frac{\overline{q}}{T_{w,i} - T_f}
\]

Here, temperature index \(T_{w,i}\) and \(T_f\) refers to the inner wall and bulk fluid temperature respectively. It cannot be measured directly and need some special care. A comprehensive description of the method is given in the next sections.

#### 4.5.1 Test section wall temperature

Recapitulate that thermocouples are glued to the outside of the test section; however, definition of the heat transfer coefficient is based on the surface of heat transfer interface. Thus, the inner wall temperature values have to be derived from the thermocouples placed on the test section outer wall surface (Chiapero2013). With the assumption of no heat loss and negligible heat flow in axial direction, the steady state equation for heat conduction through the tube wall is given by

\[
\frac{1}{r} \frac{d}{dr} \left( r \frac{dT}{dr} \right) + \frac{q^{000}}{k_w}
\]

Where \(r[m]\) is the length in radial direction, \(q^{000}[W/m^3]\) is the volumetric heat generation, and \(k_w[W/m^2K]\) is the thermal conductivity of the tube wall. The boundary conditions are no heat flux, and a known temperature \((T_{w,0})\) at, the outer surface. Integrating and solving for the inner wall temperature yields

\[
T_{w,i} = T_{w,0} + \frac{q^{000}}{4k_w} (R_0^2 - R_i^2) + \frac{q^{000}}{2k_w} R_0^2 \ln \left( \frac{R_0}{R_i} \right)
\]

\(R_0\) and \(R_i\) denotes the outer and inner radius of the heated tube. The volumetric heat generation is assumed to be uniform and can be rewritten to the following form

\[
q^{000} = \frac{P_{el}}{\pi (R_0^2 - R_i^2) \Delta z}
\]
4.5. Global HTC

With $P_d$ being the total applied electrical power and $\Delta z$ being the length of the heated section. Combining the last two equations gives the final expression for calculating the inner wall temperature.

$$ T_{w;i} = T_{w;0} + \frac{P_d}{4\pi k_w \Delta z} \frac{R_0^2}{R_i^2} \frac{R_0}{R_i} \ln\left(\frac{R_0}{R_i}\right) $$

This result is implemented in the MatLab scripts calculating the heat transfer coefficient.

4.5.2 Calculating the fluid temperature

The fluid temperature was calculated from the inlet temperature, inlet pressure, and total heat flux supplied, using a steady-state thermodynamic equilibrium model. An approach as simple as possible was chosen rather than implementing features such as two phase distributed pressure drop, non-equilibrium thermodynamic models or fancy numerical schemes.

A homogeneous flow model was chosen for its simplicity, assuming that the two-phase flow is well mixed. The slip ration, defined as the ratio between gas and liquid velocity, is then (by definition) assumed to be unity (non-slip condition). This is a fair assumption since the high Reynolds numbers of all experimental cases are associated with a great deal of turbulent mixing caused by Eddies diffusion. It also makes sense as the heat transfer coefficient is based on the bulk fluid temperature.

Any effects of non-equilibrium thermodynamic are disregarded, even though the time for phase transition to occur is limited.

Starting with the distance, velocity and time formula

$$ z = vt $$

Changing it to incremental form and rewriting the velocity gives

$$ \Delta z = v \Delta t = \frac{\dot{V}}{A_C} \Delta t = \frac{G}{\rho} \Delta t $$

Next to come is discretization in time and space. Notice that the upcoming time step is based on the current density

$$ t_{n+1} = \rho(n) \left( z_{n+1} - z_n \right) $$

This gives the time a fluid particle spends in one of the infinite small control volumes, commonly referred to as grid cells.
The energy balance contains the enthalpy $h(P,T)$ which will later be used to finally determine the temperature:

$$ \dot{m} \Delta h = q $$

The mass entering a cell is equal to the mass exiting the same cell, guaranteeing mass conservation in this steady state model.

$$ \dot{m} = \rho A c v $$

Combining the two equations above contains the enthalpy change of the fluid inside a single cell.

$$ (\rho V) \Delta h = q^0 A_s \Delta t $$

The test section is a tube with cylindrical geometry.

$$ \rho \pi d^2 dx \frac{\Delta h}{4} = q^0 (d \pi dx) \Delta t $$

Reorganizing and particularising:

$$ h_{n+1} = h_n + \frac{q^0 (t_{n+1} - t_n)}{d} $$

Finally, the two discretized equations, time and state (enthalpy) equation were implemented in a Matlab script on the following form:

$$ t_{n+1} = t_n + \frac{\rho(n)}{G} (z_{n+1} - z_n) $$

$$ h_{n+1} = h_n + \frac{q^0 (t_{n+1} - t_n)}{d} $$

The scheme is first order explicit in both time and thermodynamically state. Relative small steps were used to mitigate the adverse numerical effects, in particular numerical diffusion, such simple schemes tend to introduce. The heat flux is uniform and the diameter remains the same. The temperature at any incremental position can finally be found from the computed enthalpy and test section inlet pressure.

$$ T_n = f(p, h_n) $$

The described scheme makes it possible to evaluate the fluid temperature at any position in the test section based on the geometry, a known inlet condition (temperature, pressure and mass flow rate) and the heat input. Other quantities, such as vapour quality and mean fluid particle residence time (transit time or tau) can also be acquired from this model.

This simple unambiguous, textbook like, approach for computing the fluid temperature was chosen by practical reasons. In the end, the heat transfer
coefficient will always be a computed or derived value, since it cannot be measured directly.

4.6 Local HTC

Heat transfer performance will also be evaluated and quoted locally for two locations, namely the thermocouples at position 6 and 10 (see figure 3.2). These two location feature four external thermocouples placed on top, bottom and both side of the tube in addition to an internal thermocouple measuring the in-fluid temperature.

The heat transfer coefficient can hence be calculated from the actual measured fluid temperature rather than the modelled. Measurements in these two particular points will therefore be given special attention.
Chapter 5

Background experimental work

The main set of proper experimental results that was achieved in this project represents only a small portion of all the work that had to be carried out with the experimental facility. The learning process required in order to achieve accurate results is also part of the work behind this project, as well as the time spent with experiments that for several reasons were either not reliable or unachievable under the desired conditions.

The following chapter gives a brief explanation on how the learning process and pre-work was conducted as well as the different circumstances that led to discard other experiments.

5.1 Learning process

The learning process involved developing fluency with the facility. The different inputs that control the regulation of the fluid have an effect on the output that varies both in the strength of the effect and the time that it requires depending on the conditions of the flow. Thus, different experiments with no other aim than to develop experience in handling the facility were conducted.

The conditions set for these experiments were the same as in Deng, Fernandino, and Dorao, 2016, were the same facility at the Department of Energy and Process Engineering at NTNU was used. Therefore, the experimental results in Deng, Fernandino, and Dorao, 2016 served as a reference to be compared with the results obtained along the learning process. Once similar results with comparable quality (in terms of accuracy and reliability) were achieved, it was considered that enough experience in working with the experimental facility had been gained in order to conduct new experiments.

However the learning process as a particular stage was terminated here, many other aspects of the facility were still to be learned as new conditions required some different approaches.
5.2 Pre-work

Experiments in Deng, Fernandino, and Dorao, 2016 were made with varying heat flux, a different approach was intended for this study. Constant heat flux was desired when sweeping along decreasing qualities. In order to do this, part of the heating section had to be maintained with constant power while the previous heaters were required to vary in order to show results for different qualities.

In a first approach the last three heaters were maintained constant while the two first heaters were set to vary in power in order to control the quality, they were used as "pre-heaters". However, this method presented a disadvantage, setting a high fixed power in the last three heaters meant that no matter how low the pre-heaters were set in power, lower qualities could not be achieved due to the quality increase experimented in the fixed heating section. On the other hand, setting a low fixed power in the last three heaters prevented from achieving higher qualities since the power that can be supplied by the heaters is limited, as mentioned in chapter 3.

For this purpose it was studied the possibility of using only one heater with fixed power. The last heater was the one set to be constant while the other four were used as pre-heaters. Results were compared to the ones obtained with the previous method (three heaters with constant power) and showed the same values, proving this method as reliable as the previous one.

Proceeding with four pre-heaters allowed for a larger range of possible experiments but still, limitations were found under certain conditions as will be explained in the following section.

5.3 Limitations

The pressure inside the loop was not changed in any of the experiments. Variation of mass flux and heat flux were the object of study and for certain values of both variables the facility proved unable to work under this conditions.

Higher mass fluxes required as well higher heat fluxes in order to achieve a vapour quality value over 1 in the test section. Mass flux of \( G = 500 \text{ kg/m}^2\text{s} \) was the highest value tested with the facility and proved infeasible. In order to achieve qualities above 1 with the fixed heater at the maximum heat flux experimented \( (q^0 = 47.7 \text{ kW/m}^2\text{) which corresponds to a power of } Q = 300 \text{ kW for the heater} \), the pre-heaters had to yield a power over \( 320 \text{ kW} \) each one. This power proved unbearable by the pre-heaters that after few minutes would stop working under these conditions for safety reasons due to overheating.

For the same reasons, the conditions of \( G = 400 \text{ kg/m}^2\text{s} \) and \( q^0 = 15.9 \text{ kW/m}^2 \) in the last heater, also proved infeasible for higher qualities. Thus, the experimental data is limited by the combination of high mass flux and low heat flux at this value, and the limiting experiment with highest mass
5.4 Errors and malfunctions

The flux/heat flux relation presented in the main set of experimental data was $G = 400 \text{kg/m}^2 \text{s}$ and $q_0^{\text{in}} = 31.8 \text{ kW/m}^2$.

Lower mass flux than the ones that will be presented in the next chapter with experimental results were also tested. In this case, experiments with $G = 100 \text{kg/m}^2 \text{s}$ proved too unstable. Conditions in the high quality region were observed to vary out of the range determined for reliability on the results when logging the experiments. Therefore they are not presented amongst the results.

5.4 Errors and malfunctions

As was mentioned in chapter 4, under certain conditions the facility is likely to suffer DWO and vapour entrainment between the two flow meters (leading to inaccurate measuring of the flow). Learning how to avoid these phenomena was based on trial and error. Many experiments had to be discarded due to appearance of DWO or differing measurements of the flow meters until different approaches, that helped on avoiding these deviations (explained in chapter 4), were developed and systematically used in the following experiments.

Malfunctions of the facility also occurred in several occasions and incremented the work load required to achieve the desired experimental results:

- **Shutdown of chiller K6** due to lack of glycol led some inaccurate experiments that had to be discarded. The problem was solved by sealing the leakage that had generated the lack of glycol and refilling the tank.

- **Changes in the electric grid** that supplies power to the facility were found to cause an overload depending on the order in which the different features of the facility were started. Changing this order provided with a temporal reliable solution while the grid arrangement was fixed.

- **Shutdown of chiller K6** due to unknown reasons was observed on the last experiments after functioning for a long period of time. Some experiments had to be completely repeated because of this while in others the chiller was immediately turned back on without producing any perceivable deviation.

Apart from errors due to malfunctions of the facility, mistakes by the author of this work when working with the facility also occurred and in various cases compromised the experiments, which had to be repeated.
Chapter 6

Experimental Results

This chapter provides an overview of the main experimental results. The different experiments were conducted under a pressure of 550kPa (corresponding to a saturation temperature of 18.7°C) and varying heat fluxes and mass fluxes. The range of conditions covered by the main set of experimental results can be appreciated in table 6.1. The results on the HTC provided by these experiments are shown in figure 6.1 which provides with a general outlook. For a more organised and classified visualization of the results, they will be plotted in smaller groups over the next sections of this chapter, allowing for a more detailed appreciation of the results.

<table>
<thead>
<tr>
<th>( q^0 ) = 41.7kW/m²</th>
<th>( q^0 ) = 31.8kW/m²</th>
<th>( q^0 ) = 15.9kW/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G = 400kg/m²s )</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>( G = 300kg/m²s )</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>( G = 200kg/m²s )</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>

**Table 6.1:** Range of conditions presented in the main set of experimental data

As a general appreciation it can be seen in figure 6.1 how the experiments mainly differ before dryout. Even if dryout is encountered at different vapour qualities and HTC values, after dryout inception the behaviour is quite similar, showing an abrupt fall of the HTC until mist flow is reached. For this mist flow regime, the differences between experiments are negligible compared to the differences before dryout inception.

6.1 Study of the effect of mass flux

The variation of the HTC with the mass flux is perceptible only after a certain vapour quality has been reached. This value for the vapour quality depends on the heat flux. For the highest heat flux experimented (\( q^0 = 47.7 \) 47.8kW/m²) the HTC does not show a noticeable dependence on the mass flux until a vapour quality of approximately 0.8 has been reached. On the other hand, in the set of experiments conducted under the lowest heat flux (\( q^0 = 15.9kW/m² \)) the HTC shows a dependence on the mass flux from vapour qualities of 0.4.

This dependence not only is perceptible from lower qualities for lower heat fluxes but also, is stronger for lower heat fluxes: The difference in the HTC
that the experiments under the lowest heat flux show at a quality of 0.8 is much larger than the difference shown for the highest heat flux at the same quality value.

Nevertheless, when perceptible, the main effect that the mass flux has is an increase of the HTC with increasing mass flux.

Experiments under same mass flux and different heat fluxes can be observed in figures 6.2; 6.3; 6.4. As a result of the behaviour of the mass flux with the vapour quality that was stated in the previous paragraphs, it can be observed how experiments with same mass flux tend to become more similar as the quality increases and how this similarity becomes more noticeable for higher mass fluxes.

The profile presented by the experiments also changes with the mass flux. While experiments under lower mass flux present a more planar profile, higher mass flux changes this profile with the appearance of a slope at lower qualities which later becomes planar until another increase of the HTC before dryout inception can be observed. This peak before dryout is also seen to be dependent on the mass flux. For simplicity, the point at which the sharp increase starts will be from now on referred to as pre-dryout, using the same name as in Deng, Fernandino, and Dorao, 2016 were this trend was first observed.

It can be seen how for higher mass flux and under the same heat flux, the increase of the HTC from pre-dryout becomes sharper and more abrupt. For example, for the cases under constant heat flux of $q_{00} = 31.8 \text{kW/m}^2$, the experiment under the lowest mass flux shows an insignificant increase after pre-dryout, while the cases with intermediate and highest mass flux

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**Figure 6.1:** Main set of experimental data on HTC obtained in this project.
perfectly show this increase and with a higher slope at the highest mass flux. Furthermore, the vapour quality at which the pre-dryout is encountered also changes with the mass flux, showing that for higher mass fluxes pre-dryout is encountered at lower vapour qualities.

When focusing the dryout region, at dryout inception a higher mass flux implies higher HTC, while at dryout completion mass flux does not seem to have an effect on the HTC. On the other hand, vapour quality at dryout inception does not show a clear change with the mass flux, while vapour quality at dryout completion is seen to diminish with the mass flux.

![Figure 6.2: Experimental HTC results for the lowest mass flux (G = 200) under three different heat fluxes](image)

### 6.2 Study of the effect of heat flux

The variation of the HTC with the heat flux is significant for the different mass fluxes experimented and along all the quality range of each curve. This proves an important contribution of the nucleate boiling mechanism to the heat transfer. This dependence on the heat flux, opposite to the dependence observed on the mass flux, is stronger for lower qualities and also for lower mass fluxes as can be observed when comparing the HTC difference between curves in each of the figures 6.2, 6.3 and 6.4.

Thus, experiments under same mass flux and different heat fluxes, show more similar HTC results as the quality increases. For higher qualities convective boiling contribution appears combined with the nucleate boiling contribution and the dependence on the heat flux is therefore reduced as mass flux becomes an influential factor as was explained in the previous section.
The profile presented by the different curves also changes with the heat flux while maintaining the same mass flux. Higher heat flux is seen to imply a more planar profile. For lower heat fluxes a slope is found more markedly at lower qualities. After pre-dryout, for the lowest mass flux case the sharp increase is found steeper for the lower heat flux while for the intermediate and high mass flux case this effect is not clearly observed. The vapour quality at which pre-dryout occurs is also not observed to obey a clear response to the variation of the heat flux.

When focusing the dryout region, at dryout inception a higher heat flux implies higher HTC, while at dryout completion heat flux does not seem to have an effect of the HTC. With regard to the quality at which they occur, dryout inception is observed to occur at a lower vapour quality for increasing heat fluxes while the vapour quality at which dryout completion occurs does not show a relation with the heat flux.
6.2. Study of the effect of heat flux

Figure 6.4: Experimental HTC results for the highest mass flux ($G = 400$) under two different heat fluxes.
Chapter 7

Discussion

The primary difficulty in an investigation lies in the proper interpretation of results once they are obtained. The literature survey serves as a guide to pinpoint the most important parameters. The methods chapter gave an exhaustive description of the choice of analytical model obtaining a heat transfer coefficient and its implications. Experimental data is already presented in the previous results chapter. Main results will be used again for further interpretation and discussion of its significance. The following section will provide in-depth discussion of these results, attempting to explain them, compare them to knowledge in the current up to date literature, and map out their practical significance.

7.1 General aspects

It was already mentioned on the previous section how in the experiments presented the heat flux has a much larger repercussion on the HTC than the mass flux and how this repercussion is more noticeable for lower vapour qualities.

Recalling what was stated at the beginning of chapter 2: Convection is often distinguished as the dominant heat transfer mechanism when the HTC is almost independent on heat flux but strongly dependent on mass flux and vapour quality; Nucleate boiling is distinguished as the dominant heat transfer mechanism when the HTC is nearly independent on the vapour quality and mass flux and strongly dependent on heat flux.

Distinguishing amongst the experimental results, it can be seen how convection is never dominant. Nucleate boiling on the other hand can be distinguished as the dominant heat transfer mechanism at lower qualities, specially for lower mass flux and higher heat flux cases. As a matter of fact, the case processed under the lowest mass flux and highest heat flux (the upper curve in figure 6.2) reflects nucleate boiling as the dominant heat transfer mechanism until dryout inception.

Comparing with cases under similar conditions and with similar measuring methods (da Silva Lima, Quibén, and Thome, 2009; Grauso et al., 2013; and Chiapero, Fernandino, and Dorao, 2014), the results showed in these experiments show a much larger nucleate boiling contribution. If we take
a look back to figures 2.3 and 2.5, we can appreciate a much larger convective boiling contribution (larger dependence on mass flux) only comparable with the two cases experimented under the lowest heat flux of this project.

Chiapero, Fernandino, and Dorao, 2014 is the only article that presents an experimental case with a planar profile as the ones that have been found in this work. It can be seen in figure 7.1 where the experimental results are represented with blue crosses.

**Figure 7.1:** Experimental results from Chiapero, Fernandino, and Dorao, 2014. Blue crosses show the experiment under $G = 297.7\text{kg/m}^2\text{s}$; $T_{sat} = 34.3^\circ\text{C}$; $q'' = 20\text{kW/m}^2$.

A high saturation temperature of $T_{sat} = 18.7^\circ\text{C}$ was used in this work’s experiments and this has been mentioned several times in the literature review to increase the nucleate boiling contribution. However, the main difference between the experiments presented in this work and previous experiments is the heat flux that has been used. While the heat fluxes used in the cited articles were always below $20\text{kW/m}^2$, the heat flux used in this project ranges from 15.8 to 47.8 kW/m$^2$. This means that only the lower curves of figure 6.1 are at a similar heat flux as those found in the cited articles. On the other hand the upper curves under a heat flux of $47.8\text{kW/m}^2$ are far away from previous experimented conditions and, thus, represent a completely new behaviour in which nucleate boiling seems to be the dominant heat transfer mechanism up to a vapour quality of almost 0.8.

This new behaviour defies statements made in other articles such as Greco, 2008 where it was said that the HTC always increases with mass flux and that this increment is actually exponential. In the results presented in this work it can be seen how this statement is only correct when there is a significant effect of the nucleate boiling contribution. Furthermore, it was found in this article’s experimental results together with Grauso et al., 2013 that, after a
local minimum that may be present at low vapour qualities, and until dry-out inception, the HTC always increased with vapour quality. However the large regions of nucleate boiling contribution in the experiments presented in this work reflect a planar profile in which the HTC is constant for a significant range of vapour qualities.

7.2 Dryout

Dryout was, in the presented experimental results, measured cautiously, allowing to visualize in detail this gradual transition between annular flow and mist flow.

In da Silva Lima, Quibén, and Thome, 2009 the quality at which dryout occurs was said to decrease with mass flux and heat flux. The results shown in this work corroborate an earlier dryout inception with an increasing heat flux, but mass flux variation does not show a clear effect on the vapour quality at which dryout inception occurs.

Deng, Fernandino, and Dorao, 2016 also presented results in which mass flux does not show an effect on the vapour quality at which dryout inception occurs (figure 7.2). At the same time these experiments showed a larger nucleate boiling contribution than convective as the ones presented in this work. Thus, it makes sense that, due to this smaller convective boiling contribution, mass flux does not have a significant effect on the vapour quality for dryout inception. Further experiments would be required to prove this hypothesis indicating that the effect of mass flux on dryout quality is dependent on the strength of the convective boiling contribution.

![Figure 7.2: Experimental results from Deng, Fernandino, and Dorao, 2016 under different mass fluxes](image-url)
While the quality at which dryout inception occurs was not observed to vary with the mass flux. Vapour quality at dryout completion was observed to slightly decrease with mass flux. This trend was also found much stronger in da Silva Lima, Quién, and Thome, 2009.

The reason behind this contrast might be that while the independence of dryout inception quality with the mass flux was said previously to occur due to the strong nucleate boiling contribution. In the mist flow region, nucleate boiling disappears. This might be why mass flux has an effect on the quality at which dryout completion occurs but not on the quality at which dryout inception occurs.

If we were to compare the experiments from da Silva Lima, Quién, and Thome, 2009 in figure 2.3 with the ones in this experiment under similar conditions of heat flux, mass flux and saturation temperature, a great difference can be observed in the quality at which dryout occurs. While the case under $G = 300 \text{ kg/m}^2 \text{s}; q^0 = 17.5 \text{kW/m}^2$ and $T_{\text{sat}} = 20^\circ \text{C}$ shows a dryout inception quality of 0.85, a similar case presented in this work with $G = 300 \text{ kg/m}^2 \text{s}$ and $q = 15.9 \text{kW/m}^2$ presents a dryout inception quality of 0.95. The only difference between this two cases is that experiments in da Silva Lima, Quién, and Thome, 2009 were performed with a copper tube while the experiments presented in this work were performed with a stainless steel tube.

If we recall from the literature survey in chapter 2, it was mentioned that the heat transfer coefficient is seen to peak at higher vapour qualities for stainless steel. However, this was taken from Pike-Wilson and Karayianis, 2014 where experiments were not conducted for R134a, but for R245fa. Thus, this comparison presented in the previous paragraph indicates that this effect might be also important for R134a.

Moreover, articles Grauso et al., 2013 and Deng, Fernandino, and Dorao, 2016 (both used stainless steel tubes) also show a quality for dryout inception around 0.95 or higher. Further proving the mentioned effect of the material used.

However, this conclusion must be regarded cautiously as there is another factor that differs in both experiments and is the tube diameter used. While da Silva Lima, Quién, and Thome, 2009 used an internal diameter of 13.84mm, it was 5mm for this work.

So far in this section it has been mentioned the variation of the vapour quality at which dryout inception and completion occur, without treating the HTC that is reached for these points.

In da Silva Lima, Quién, and Thome, 2009 were convective heat transfer was dominant, HTC at dryout inception was said to increase with mass flux and decrease with heat flux. This work also shows an increase of the HTC at dryout inception with mass flux (although not as strong due to the small convective boiling contribution) but presents the opposite result with heat flux than the cited article.
The reason behind this is that, in da Silva Lima, Quibén, and Thome, 2009 the nucleate boiling contribution is so small that the HTC variation with the heat flux is almost negligible at vapour qualities close to dryout. At the same time, dryout inception occurs at an earlier vapour quality with increasing heat flux and the HTC increases with quality when approaching dryout. Thus, a dryout inception at a lower quality results in a lower HTC when dryout inception occurs.

The experimental results presented in this work also show an increase of the HTC with vapour quality close to dryout, as well as an earlier inception of dryout with increasing heat flux (as was previously commented in this section). However, the main difference is the strong influence of the heat flux in the HTC even at dryout inception. While HTC at dryout inception for a higher heat flux case may be slightly lower than it would if dryout inception had occurred at the same vapour quality as a similar case with lower heat flux, this difference is much smaller than the HTC that both cases have right before dryout due to the heat flux difference.

Thus, this behaviour indicates that whether heat flux increase results in a higher or lower HTC at dryout inception, depends on the strength of each of the heat transfer mechanisms over the other one. Therefore, with dominant convective heat transfer mechanism it appears that HTC diminishes with heat flux, however, as nucleate boiling gains strength in the process this effect may fade until nucleate boiling contribution grows strong enough to produce the opposite effect, increasing the HTC at dryout inception with increasing heat flux.

7.3 Sharp increase before dryout

It was mentioned in chapter 2 that Deng, Fernandino, and Dorao, 2016 was the first and only other article in the literature review observing a sharp increase before dryout. It has been already commented on the previous chapter regarding experimental results how this behaviour is also observed in this work. Thus, special focus was made on this feature due to the novelty that it supposes.

Deng, Fernandino, and Dorao, 2016 mentioned that this sharp increase is caused by a slight decrease on the wall temperature. For this purpose, figure 7.3 shows simultaneously the variation of the HTC and the difference between inner wall and saturation temperatures ($\Delta T = T_w - T_{sat}$), against the vapour quality. The saturation temperature keeps almost constant during the process so that $\Delta T$ can also represent the variation of inner wall temperature. These results show a direct relation between the HTC and the temperature difference $\Delta T$, as the experiments published in Deng, Fernandino, and Dorao, 2016.

Furthermore, the article states that a possible reason for this improvement on the HTC might be that at high vapour qualities, the vapour velocity is quite high and the film is very unstable until the dryout occurs. Meanwhile, the interfacial shear between the vapour and the film enhances the heat transfer. On the other hand, the vapour of high velocity and the high
wall heat flux may contribute to the entrainment, which reduces the film thickness and the heat transfer coefficient increases.

If this hypothesis was true, an increase in the vapour velocity enhances this phenomena. Thus, higher mass fluxes would result in more pronounced peaks. In figure 7.3 the process can be observed for two different mass fluxes and, in agreement with the hypothesis, both the HTC and the temperature difference $\Delta T$ show a more pronounced change for the higher mass flux case.

Moreover, Deng, Fernandino, and Dorao, 2016 also mentions that the vapour quality at which pre-dryout (the starting point of the sharp increase) occurs, also depends on the mass flux. This statement is based on the experimental results published in this article for two different mass fluxes. Those were already commented on the dryout section and plotted in figure 7.2, were pre-dryout can be found for a quality of 0.82 for the higher mass flux and of 0.75 for the lower mass flux. However, this behaviour is not observed in the experiments presented in this work. Further study on this region would be required in order to understand this difference and the mechanisms impulsing this HTC enhancement.
Chapter 8

Conclusion

In the present study, the heat transfer coefficient for boiling R134a in a tube was experimentally evaluated for a pressure of 5.5 bar (saturation temperature of 18.7°C); mass fluxes ranging between $G = 200 \text{kg/m}^2\text{s}$ and $G = 400 \text{kg/m}^2\text{s}$; and specially high heat fluxes ranging between $q^0 = 15.8 \text{kW/m}^2$ and $q^0 = 47.8 \text{kW/m}^2$ in a 5mm internal diameter tube.

Due to the high heat fluxes used, the experimental results show a strong nucleate boiling contribution, quite uncommon in previous studies on the topic.

This strong nucleate boiling contribution appears to yield similar results for experiments under the same heat flux, this similarity increases with the heat flux and decreases with the mass flux and vapour quality. Therefore, results under the same heat flux and different mass fluxes only show an increase of the HTC with mass flux after a certain vapour quality value. Thus, opposing to previous experimental results published on the topic were, due to the strong convective boiling contribution HTC showed a noticeable increase with the mass flux for most of the quality range.

At the same time a more planar profile is found that terminates with a sudden sharp increase before dryout inception. This behaviour is more pronounced for lower mass fluxes and higher heat fluxes, therefore, when nucleate boiling contribution is dominant.

Measuring with small quality increments for high vapour qualities allowed for a detailed visualization of the HTC during the dryout region.

In agreement with previous studies, dryout inception occurred at lower qualities with increasing heat flux. However, an increase of this dryout inception quality with the mass flux was not observed in the results as it was in previous studies. A possible reason may have been that due to the smaller convective boiling contribution presented in these experiments, the mass flux does not have a noticeable effect on the quality at dryout inception. For the same reasons it is believed that the HTC achieved at dryout inception for different mass fluxes did not show a strong increase with the mass flux and was more dependent on the heat flux.

However, mass flux did show a slight influence in the quality at which dryout completion occurred. As in previous publications, an earlier dryout completion was found with increasing mass fluxes. A possible explanation
for the mass flux affecting the vapour quality for dryout completion but not for dryout inception might be that at dryout inception, nucleate boiling contribution still had an strong effect, however, nucleate boiling disappears when entering the mist flow region, leaving a stronger contribution from convective boiling and, thus, of the mass flux.

Comparisons were also made with results collected from the literature review regarding the effect of the material used for the tube and the dryout quality. Pike-Wilson and Karayiannis, 2014 already studied this effect with refrigerant R245fa and concluded in an earlier dryout inception for copper tubes than stainless steel tubes. The same appreciation was made in this work with R134a, although some differences in the experiments compared do not allow for it to be a conclusive result, but an indication for further studies.

Regarding the HTC that is achieved at dryout inception, it was found to increase with mass flux although not as significantly as in previous experiments on the topic with larger convective contribution. However, completely opposite to previous results as the ones published in da Silva Lima, Quibén, and Thome, 2009. HTC at dryout inception was seen to increase with heat flux.

The reason behind this is that in previous studies with dominant convective mechanism when approaching dryout inception, heat flux did not influence the HTC at each vapour quality. On the other hand, higher heat fluxes presented earlier dryout inceptions and, since HTC also increased with quality, this earlier occurrence of dryout inception provoked that the HTC achieved at dryout inception was smaller for experiments under higher heat fluxes.

In the experiments presented in this work HTC also generally increases with quality and as mentioned earlier higher heat fluxes produce an earlier inception of dryout. However, experiments with different heat fluxes show a large difference in the HTC that they present when approaching dryout. Therefore, even if the HTC achieved for a higher heat flux case is smaller that if it had continued the same trend until a vapour quality corresponding to the dryout inception quality of a lower heat flux case, this difference is much smaller than the initial gap presented between both experiments under different heat fluxes.

Thus, this behaviour indicates that whether heat flux increase results in a higher or lower HTC at dryout inception, depends on the strength of each of the heat transfer mechanisms over the other one. With dominant convective heat transfer HTC diminishes with heat flux, but as nucleate boiling gains strength in the process this effect fades until nucleate boiling contribution grows strong enough to produce the opposite effect, increasing the HTC at dryout inception with increasing heat flux.

Finally, a sharp increase of the HTC with quality was found before dryout inception for all the cases experimented except the ones with lower mass flux and higher heat flux (stronger nucleate boiling contribution). This improvement in the heat transfer coefficient had only been reported before in
Deng, Fernandino, and Dorao, 2016 and mentioned to occur due to a slight decrease of the wall temperature. A possible reason for this phenomena was said to be that the vapour at high quality moves faster and therefore removes the heat more efficiently, meanwhile, the interfacial shear between vapour and film enhances the heat transfer contributing to this enhancement of the HTC prior to dryout.

Experiments conducted in this work presented this sharp increase in direct relation with a decrease on the wall temperature. Moreover, higher mass fluxes showed a more pronounced increase, thus, favouring the hypothesis made by Deng, Fernandino, and Dorao, 2016 on the mechanism behind this feature. Nevertheless, further studies on this characteristic are required in order to achieve a decisive conclusion.
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