Condensation on the Containment Structures

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Abstract. Condensation on the Containment Structures is a phenomenon that takes great importance at the moment in which becomes the essential mechanism for a passive safety system. From this point of view, we will focus our study on the consideration of the phenomenon only in the cases in which it constitutes a fundamental part of the performance of a safety system. This document first includes an introduction to the phenomenon in which its definition, as well as the basic aspects that have to be considered, will be depicted. In this way, it will be able to outline the phenomenon frame which provides us to know the extent and links with the relevant models, experimental data and facilities, and codes.

1. INTRODUCTION

Condensation of vapor on the limiting walls of a considerable volume is associated with two fundamental facts: heat transfer from the atmosphere, and decreasing of the vapor concentration.

Condensation on the Containment Structures is a complex phenomenon which evolves other phenomena. The relevance of this phenomenon is that it is one of the most effective passive cooling mechanisms in containments of advanced water reactors.

To deal with it, it is advisable not only to define it, but also to site it in a particular scenario (*when* it occurs) and in a particular hardware (*where* it occurs), so we can understand its *scale frame*, namely, its relationships with other phenomena (better said, the other phenomena up to their relationships with the condensation phenomenon) to the extent of being able to capture its overall performance. In this way, it will able to know which kind of experimental tests will be suitable to validate the model as well as the code where the model is implemented.

1.1. Definition

Phenomenon involving heat and mass transfer from the containment atmosphere towards the surrounding structures. This phenomenon would take place in the existing reactors in case of a primary system blowdown into the containment. However, it is highly enhanced in advanced reactors where surface temperatures are cooled externally, usually by natural mechanisms. Good examples are the designs of the AP series by Westinghouse, where the containment is made of steel that is cooled by falling water by gravity from external reservoirs placed outside the containment and an ascending air draft driven by buoyancy.

Steam condensation is largely affected by some boundary conditions. They can be split in two groups depending on how relevant are the physical dimensions of the system to assess their impact. The “scale-independent factors” are variables like the pressure, which effect could be well investigated through Separate Effect Tests (SET). The “scale-dependent factors” are those phenomena that require to be investigated in actual or scaled geometries (i.e., Integral Effect Tests, IET) since physical dimensions largely influence their quantitative effect. Examples of this kind are the AP600/1000 natural convection process at both sides of the metallic structures, and the potential concentration gas stratification.

1.2. Scenario

The phenomenon takes place during a loss-of-coolant (LOCA) or a main-steam-line-break (MSLB) accident, or any other accident that causes a coolant release into the containment. There are two facts that must be pointed out:

1. The phenomena occurring only during a severe accident will not be taken into account, i.e., aerosols presence.
2. The other phenomena that appear in the same scenario will only be considered up to their influences on the studied phenomenon.

During a DBA, large amount of steam is released to the containment. As the wall temperature is lower than its saturated temperature, the steam starts condensing on the containment walls, while the non-condensable gases are accumulated beside the film condensate layer creating an additional thermal resistance. This gas layer acts like a barrier resulting in a degradation of the heat transfer to the wall, making that the interface temperature takes a lower value as a consequence of the diffusion mass process through the non-condensable gases layer, which brings on a lower condensate mass flux.

In this brief outline of the scenario, the nearly whole of the phenomena affecting the condensation process have been mentioned:

1. The most important phenomenon is the non-condensables presence. A mass fraction of 1% or 2% can reduce heat transfer to 50% in static conditions [1]. Its performance has been well studied by many authors, and it can be reduced to a thermal resistance caused by the accumulation of the non-condensables at the interface that have been dragged by the convection stream of the steam to the interface, and also by its low water solubility at the range of temperatures in which containment condensation takes place. As the non-condensables cannot mix with the liquid, they start to accumulate creating a real barrier for the steam. This barrier causes the steam to diffuse through the non-condensable gases, so its interface concentration will be no more the result of the thermodynamic properties (pressure) of the steam in the bulk, but also the result of the diffusion mass process.
2. Not only is important the non-condensables fraction -the quantity-, but also the gases composition. If hydrogen is released to the containment, it will be a shift in the gases composition that will affect both locally and globally to the condensation phenomenon. Locally, due to the change in the diffusion coefficient and in the driving buoyancy force from the bulk to the interface. And globally, due to the hydrogen lower density, that can cause a barrier that will produce a strong decrease in the heat transfer coefficient up to 75% in the upper part (horizontal) of the containment [2].
3. Wall containment cooling. To control the wall temperature and keep it below the vapor saturation temperature, it is necessary to cool the wall transferring the steam heat to other sink.
4. The condensation on the containment walls is a heterogeneous film condensation. This means that even if we had a drop-wise condensation, this probably would evolve to the film model, and its impact would not affect to the global pressure-temperature containment response [3].
5. The turbulent nature of the liquid film flow on the walls. It is known that after the liquid flow has covered a short distance, its regime will quickly become turbulent [4].
6. The variations of the atmosphere flow regime. In a loss-of-coolant accident (LOCA) it can be distinguished two different time periods. The first one (blowdown) involves a large hot steam injection due to the vessel depressurization, which induces a great turbulence atmosphere and produces the highest values in the containment temperature and pressure. At this stage, forced convection and condensation are the most important heat transfer mechanisms. The second

period (postblowdown) can be distinguished by a much lower turbulence in the atmosphere, being the natural circulation and condensation the main heat transfer processes.

7. Other phenomena: the condensation process is a very complex phenomenon that deals with many phenomena. Among others:
    a. Suction effect, due to the momentum transfer of the steam to the film layer.
    b. Shrinkage of the film layer, due to the drag caused by the gas phase, which leads to a reduction of the film thermal resistance.
    c. Rippled structure of the film surface. The waviness effect causes an enhancement of the heat transfer.
    d. Mist formation that consists of an anticipated condensation of vapor before reaching the interface, forming liquid droplets within the gas. This effect causes an enlargement of the sensible heat transfer.
8. Parametric variations. Besides these phenomena affecting the wall condensation process, it has also to be considered the possible variations of the boundary and initial conditions, i.e., bulk temperature, wall temperature, bulk pressure, atmosphere velocity, etc.

1.3. Hardware

By hardware it is meant the place where the scenario evolves. This is a matter of concern because wall condensation is a phenomenon highly specific on the boundary conditions. So, as it will be shown below, the place where the phenomenon evolves has to be considered for a good understanding of it.

The hardware is the reactor containment provided that their structures operate as the fundamental part of the passive containment cooling system (PCCS). This means that the study will only be focused on those reactors that utilize a passive nature system to cope with the maintenance of containment integrity. So containment cooling systems based on cooler sprays, or those which use tube condensers, shall not be taken into account in this document.

Based on the information depicted, from which it is possible to clarify the limits and to contextualize the analyzed phenomenon, it can be established the nuclear plants designs concerning our phenomenon. Among others, the main nuclear power plants where condensation on the containment structures plays a key role in the containment safety system are:

AP600 & AP1000: This design utilizes a unique system to maintain the containment atmosphere pressure and temperature within design limits [5]. Figure 1 shows a schematic of the reactor containment. In the event of a postulated accident where high pressure cooling water escapes into the containment, the pressure and temperature will increase as water flashes to steam. The steam will in turn start to condense on the steel containment vessel which is initially at ambient temperature. This results in an increase in the surface temperature of the steel wall. The heating of the steel containment wall causes air from outside, due to buoyancy forces, to be drawn in through an air baffle between the concrete containment and the steel inner wall (not present in current reactors). This process, along with the release of cooling water by gravity from reservoirs situated above the containment, hold the wall temperature well below that of the internal bulk atmosphere. This temperature difference, along with a concentration difference created by the condensation of steam in the presence of noncondensable gases, sets up a natural circulation flow pattern within the containment. Steam condensation, enhanced by the turbulent natural convection, but inhibited by a noncondensable gas layer formed adjacent to the wall, should provide sufficient cooling to keep the conditions within the containment under safe structural limits.

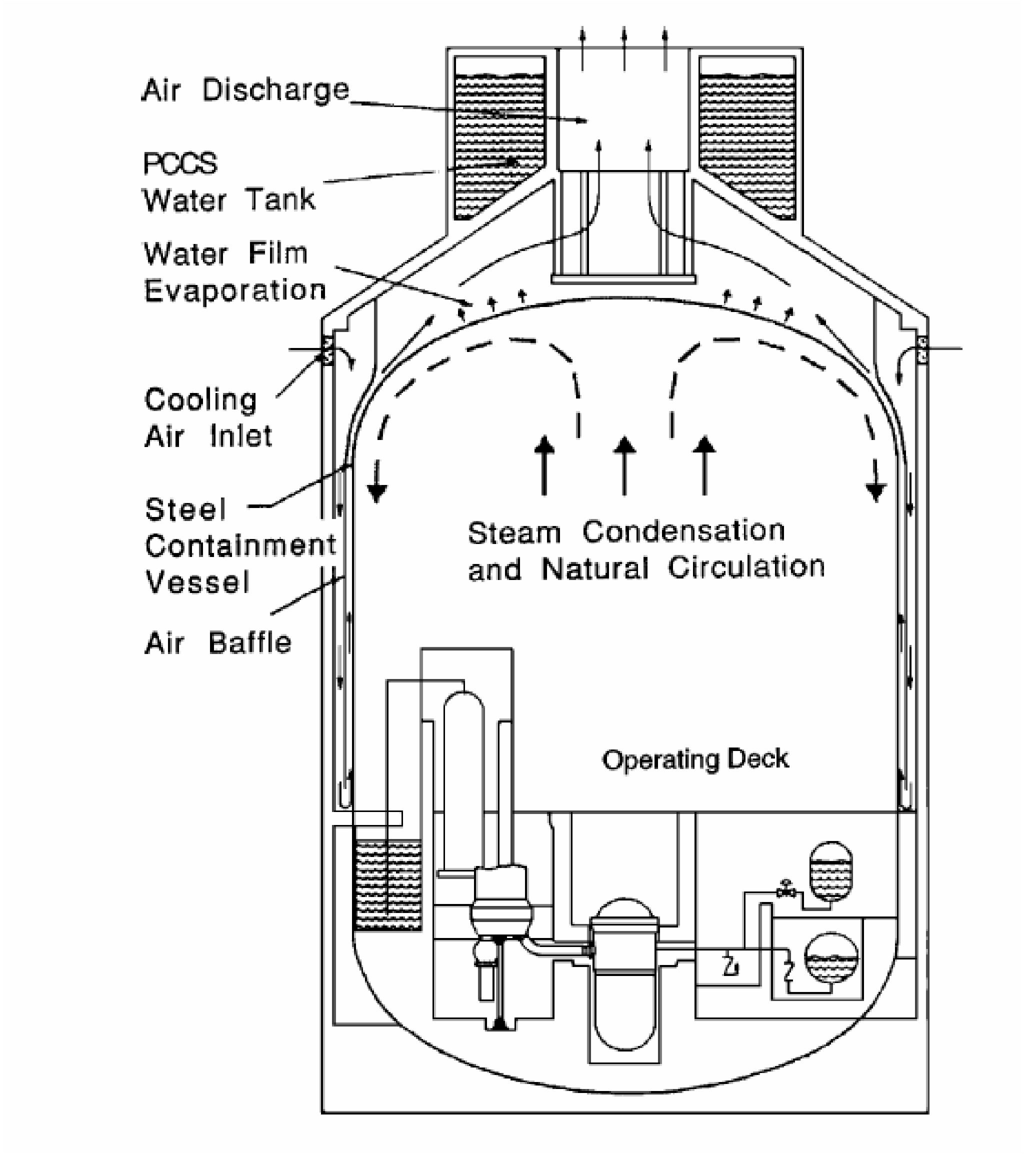

Fig. 1. Sketch of the PCCS of the AP600.

EP1000, SPWR: The EP1000 is an advanced 1000 MWe PWR design developed by Westinghouse and Ansaldo together with seven European utilities. The design follows the SPWR design, and keeps the AP600 as a basis for the auxiliary systems.

SPWR is a power uprated version of the AP600.

AC600/1000: The containment cooling system of this PWR nuclear power plant designed by the Nuclear Power Institute of China (NPIC) has basically the same features of the AP600 reactor.

2. RELEVANT MODELS FOR CONDENSATION ON THE CONTAINMENT STRUCTURES

There have traditionally been two main different approaches to model the phenomenon of condensation in presence of non-condensable gases: an empirical and a mechanistic approach.

2.1. *Empirical approach*

The empirical approach, or experimental approach, is based on deriving a correlation from experimental data recorded. The initial measurements used for the design and equipment qualification of containments were obtained by Uchida [6] and Tagami [7]. Their facility consisted of a series of metal cylinders inside 42 cubic meters chamber. Uchida made his experiments under a natural convection regime. Uchida's data have been correlated in terms of a single variable in order to obtain a total heat transfer coefficient:

$$h = 380\left(\frac{X_{air}}{X_{st}}\right)^{-0.7} \tag{1}$$

Where *h* means total heat transfer coefficient, and X_{air}, X_{st} means respectively air and steam mass fraction. The Tagami data have been differentiated in two forms: a time-period corresponding to the initial stages of a large-brake LOCA (including time-dependent energy blowdown parameters), and a second form for natural convection quiescent condition:

$$h_{steady\_state} = 11.4 + 284\left(\frac{X_{st}}{X_{air}}\right) \text{ for } 0 < m_v / m_g < 1.4 \tag{2}$$

The total heat transfer coefficient for the transient period is then:

$$h_{tot\_max} = 426\left(\frac{E_A}{t_A V_c}\right)^{0.6} \tag{3}$$

$$h_{tot} = h_{tot\_max}\left(\frac{t}{t_A}\right)^{0.5} \text{ for } t \le t_A \tag{4}$$

$$h_{tot} = h_{steady\_state} + (h_{tot\_max} - h_{steady\_state})\exp(-0.5(t - t_A)) \text{ for } t > t_A \tag{5}$$

Where E_A is a dimensional grouping of the energy added (Btu), V_c is the containment volume (ft^3) and t_A is the total time for the addition (seconds). Tagami made his experiments with a forced convection regime. As it will be said below, in these experiments bulk convective motion is small compared to those existing in a LOCA or MSLV event.

Another correlation is Kataoka's correlation [8]:

$$h = 0.43\left(\frac{X_{air}}{X_{st}}\right)^{-0.8} \tag{6}$$

Green [9] derived a correlation from the realistic full-height facility HDR E1 series data:

$$h = 316\left(\frac{X_{air}}{X_{st}}\right)^{-0.86} \Delta T^{-0.15} \tag{7}$$

For natural convection and turbulent boundary layer, Dehbi employed a finite-difference technique that permitted him to analyze a turbulent gas-vapor boundary layer inside a vertical tube. Dehbi applied the Turbulent Kinetic Energy (TKE) method to treat turbulence. Considering a suction effect that shrinks the film condensate layer, an assuming that this effect creates at the same time over the gas-vapor boundary layer a single turbulent core, in this way it is possible to neglect a secondary thin (liquid) layer.

The experiment of Dehbi et al [10] looked specifically at the effect of the containment variables at a small scale. In these experiments, they conducted some experimental work on a 3.5 m long and 0.038 m diameter tubular geometry with different pressures, mass fraction of vapour/non condensable gases (helium as a hydrogen simulant). This experiment led to the development of correlations that relied on these variables. Despite the valuable information provided by Dehbi experiments, the geometry of the facility is a drawback due to the questionable non-uniform conditions in the vessel used to perform the experiments.

Dehbi's correlation is the following:

$$h = \frac{L^{0.05}\left[(3.7 + 28.7P) - (2438 + 458.3P)\log X_{air}\right]}{T_b - T_w} \tag{8}$$

In general, the values given by empirical correlations are usually lower than the experimental values from the separate-effect-tests. Green and Almenas [11] proposed three mechanisms to account for such behaviour:

1. Theoretical models impose bulk velocities that usually are much lower than reality.
2. Formation of mist in the gas-vapor boundary layer under saturated conditions may increase the sensible heat transfer from the atmosphere to the walls.
3. The rippled nature of the condensate film also enhances the heat transfer process.

The problem of this kind of correlations is that they come from separate-effects-tests (SET). Besides the dependence of the correlation with the experimental data and facility, containments are large complex structures, and during a hypothetical coolant release, a wide range of phenomena occur. Therefore, it seems that neglect of enhancing heat transfer mechanisms by empirical correlations makes them behave in a conservative way.

An example of what it has been said is the widely used Uchida's correlation, which depends only on the ratio of mass fractions, and is one of the correlations implemented in Gothic code. Peterson [12] found out that the correlation well performance only agrees with reality if the boundary conditions are similar than those applied in the tests (pressure value, gas velocities, wall length, etc.). Otherwise, the correlation tends to underpredict the results.

2.2. Mechanistic approach

Mechanistic condensation modelling has been traditionally addressed by two different approaches: solution of conservation equations in the boundary layer without making use of the heat and mass transfer analogy in the closure relations ([13], [14], [15]), and the application of the heat and mass transfer analogy ([16], [17], [18]). According to Green and Almenas, the latter can be considered both as a theoretical and empirical approach, since the analogy use is based on theoretical foundations, and simultaneously it is needed some empirical correlations to close the model.

2.3. Field Equations

With respect to the first kind of processing, a numerical approach based on solving the mass, momentum, energy, and conservation species over the gas boundary layer and in the film boundary layer, Sparrow [13] developed the earliest investigation on condensation in the presence of noncondensables.

This kind of approach has its best on the fact that the models can account for all the existing phenomena and, as they have been not derived from experimental data, they can be used for different regimes and range of variable conditions. Its weakest point lies on the high difficulty of the model to deal with a thermal-hydraulic code: As most of the codes that model the containment are lumped-parameter codes, or codes that use large volume structures, and the condensation model boundary layer equations require the specification of local variable boundary conditions, that is to say, a high degree of nodalization, it would be complicated to implement the model in a thermal-hydraulic best-estimate code.

Sparrow developed its model considering natural convection and laminar flow, solving the mass, momentum, and energy equation for a one-dimensional liquid film, and applying a similarity transformation that stands that the velocity profile remains geometrically similar as the layer grows along the length of the surface. Sparrow also used the classical Nusselt theory [19] for the film thickness.

Minkowycz [20], following Sparrow, developed a work that included the effects of variable thermophysical properties, superheating, interfacial resistance, mass transfer due to thermal diffusion and concentration diffusion, and energy transport due to the diffusion layer.

Rose [21] gave a simpler solution for natural convection on a vertical plate, assuming concentrations and velocity profiles known. For high values of noncondensables mass fraction the results were close to Minkowycz's, but when the value becomes small, this method overpredicts heat transfer degradation.

This kind of theoretical constructions can be simplified with the appropriated assumptions. One of the most widely used in condensation on the containment structures is to assume an interfacial temperature equal to wall temperature, so considering a film layer resistance negligible (film thickness negligible considering containment volume). In the COMMIX-1D code analytical model [22], it is assumed that the volume occupied by the liquid film is very small relative to the total volume, either containment volume or the annulus between the outside containment shell and inside building wall (where there is a liquid evaporating film), so the liquid films volume are neglected. The problem in neglecting the film layer thermal resistance is that, in the case the liquid thickness was not really small, the model can overpredict the results, that is to say, go away from a conservative approach.

For forced convection with laminar boundary layer, Sparrow examined the case of forced flow over a horizontal plate. Denny [23] also studied the forced convection condensation for a vertical surface under laminar flow conditions.

What it can be shown when comparing the forced convection results with those obtained in natural convection is that the latter always yields more conservative results, far away from the experimental real values. This is because this kind of models have not accounted for the bulk velocity, which is a parameter of primary importance [11].

2.4. *Heat and Mass Transfer analogy*

As the main problem in condensation with noncondensables model is to obtain the condensation mass flux -since this is the principal heat and mass transfer mechanism-, it is possible to compute mass flux by means of a convective heat transfer formulation:

$$\dot{m}''_{cond} = \frac{h_{cond}\left(T_b - T_i\right)}{h_{fg}} \tag{9}$$

Where T_b and T_i mean bulk and interface temperature, h_{cond} is the condensation heat transfer coefficient -which becomes now the main unknown quantity-, and h_{fg} is the phase change enthalpy.

In this way, the total heat and mass transfer problem would be completed considering a heat balance in the interface with a steady state condition:

$$h_{film}(T_i - T_w) = (h_{conv} + h_{cond})(T_b - T_i) \tag{10}$$

Here, h_{film} is the liquid heat transfer coefficient, and h_{conv} is the gas convective heat transfer. Colburn and Hougen [24] were the first in suggesting this heat balance, as well as the gas-vapor boundary layer making up of two parallel components.

Because of the fact that the interface values appear in the equations, the theoretical models have usually an iterative nature, which would constitute a slow-down if the model were implemented in a thermal-hydraulic code.

As the integration of the one-dimensional gas-vapor diffusion equation -considering also the convective term- over the boundary layer thickness yields the mass flux [25], it would be enough to express, with the help of heat and mass transfer analogy, this mass flux as a mass transfer coefficient times a concentration difference.

The different heat and mass transfer models use to differ among them mainly depending on how mass transfer coefficient and so the condensation heat transfer is computed, and secondary, on which simplifications and correlations are used. Regarding on the mass transfer (mass flux) expressions, a recent sensitivity study has been performed, where different mass flux formulations were compared to experimental data, basically, the Chilton and Bird ([26], [27]) formulation and the Collier and Stephan formulation ([25], [28]). These two expressions differs on the mass transfer coefficient, where the Chilton coefficient has considered the heat and mass transfer correction for suction effects, and also on the way Fick's law is derived. Collier considered film's theory hypothesis, which states that the convective noncondensable gases term towards the interface is equal in magnitude to the diffusion term towards the bulk. These differences makes that the Collier's expression gets values lower than 40% respect to Chilton's. But as the mass flux expression is embodied in the condensation model, usually this term is not separately considered.

One of the most used models is the one proposed by Collier. This author used mass diffusion film theory hypothesis developed by Stephan [28], to obtain the condensation mass flux, together with the HMT to obtain the condensation mass transfer. Collier made used of a Dittus-Boelter correlation together with the HMT analogy. The film’s mass diffusion theory is also used to the mass transfer models implemented in the CONTAIN [29] and COMMIX-1D codes.

Other widely used condensation heat transfer coefficient makes use of the Peterson condensation conductivity [17]. The author used the integration mentioned above -in the film’s mass diffusion form- to obtain an average gas-vapor velocity and with the use of the HMT yielded condensation conductivity. The difference with Collier's model lies in the particular form of Peterson’s coefficient, based on both the use of the ideal gas law and the Clausius-Clapeyron equation to set the jump boundary pressures in a jump boundary temperatures, in such a way that it is simpler to implement it in an algorithm to compute the total heat transfer coefficient. Finally, instead of using directly a mass transfer coefficient to compute the condensate mass flux, he obtained a heat transfer coefficient based on an effective condensation thermal conductivity:

$$k_c = \frac{1}{\phi}\left(\frac{h_{fg}^2 P_0 M_v^2 D_0}{R^2 T_0^2}\right) \tag{11}$$

Where D is the diffusion coefficient evaluated at a reference temperature T_0 and pressure P_0, M_v is the vapor molar mass, R is the universal gas constant, and Φ is a gas/vapor logarithmic mean concentration ratio, given by:

$$\phi = \frac{x_{g,ave}}{x_{v,ave}} = -\frac{\ln\left[(1-x_{gb})/(1-x_{gi})\right]}{\ln\left[x_{gb}/x_{gi}\right]} \tag{12}$$

Finally, as Collier's model, Peterson related this term with an empirical correlation together with the HMT, using also, as Collier suggested, a Dittus-Boelter correlation for turbulent regime.

Peterson’s conductivity was used and modified in Herranz’s model [30] to take into account that the specific volume change along the gas-vapor boundary layer shows a substantial variation in the temperature range of interest:

$$k_c = \frac{1}{\phi}\left(\frac{h_{fg}^2 P_0 C_v M_v^2 D_0}{R_v T_i^2 T_{ave}}\right) \tag{13}$$

Where C_v is the vapor molar concentration, and $T_{ave} \approx \frac{T_b}{T_i}$.

Another interesting aspect of the Herranz model is the Grashof number form that is expressed as follows:

$$Gr = \frac{g\rho_{gb}(\rho_{gi} - \rho_{gb})L^3}{\mu^2} \tag{14}$$

In this way, it is possible to consider not only the temperature difference but the composition differences, so the driving forces (buoyancy forces) are not underpredicted.

Also Vernier [31] had already proposed this kind of formulation for the Grashof number:

$$Gr = \frac{g\rho_{gb}L^3}{\mu^2}\left[\beta(T_b - T_i) + \gamma(X_{gi} - X_{gb})\right] \tag{15}$$

Where $\frac{1}{\gamma} = \frac{M_g}{M_g - M_v} - X_{gb}$

Once the condensation conductivity is computed, it is possible to obtain the condensation heat transfer coefficient by means of an empirical correlation through the heat and mass transfer analogy, substituting the Nusselt and Prandtl numbers for Sherwood and Schmidt numbers.

These models have also in common the arrangements that have to be done in order to use the analogy adequately. For this purpose, a correction factors for high mass transfer rates have to be taken. Usually, the form of these factors is taken from Bird [27]. Moreover, most of the authors also take into account correction factors for considering the ripple film structure, mist formation, and for the film layer modeling, which is most always taken by Nusselt and corrected by introducing the interfacial shear stress and the subcooling of the film layer [32]. All of these factors accounted for are mechanisms that increase the heat transfer.

Corradini [33] made an analysis considering a turbulent gas-vapor boundary layer either for natural and forced atmosphere convection. The model concludes that the film layer thermal resistance is negligible when comparing to that of the gas-vapor boundary layer. Due to the containment dimensions, where the film will quickly become turbulent, this conclusion would be even more apparent.

For his analysis, Corradini used the Reynolds analogy and extended it to a heat and mass transfer analogy, but instead of substituting the non-dimensional numbers directly (Sherwood by Nusselt; Schmidt by Prandtl), he developed the analogy as Rohsenow and Choi suggested [34], arriving to the following results:

$$\begin{aligned} Nu_{FC} &= 0.037 Re_L^{0.8} Pr^{1/3} \\ Sh_{FC} &= 0.037 Re_L^{-0.2} Sc^{-2/3} \end{aligned} \tag{16}$$

Where FC stands for forced convection. For natural convection, the model theoretical development follows the same guidelines, being the liquid velocity profile calculation the only change. For natural convection, the velocity is not imposed, so an additional consideration is made considering a turbulent film regime. Corradini took Eckert and Jackson work [35] to compute the interfacial velocity for the turbulent film boundary layer, assuming similar energy and momentum profiles. The turbulent film velocity profile was introduced in the film coefficient heat transfer, so the negligible character of the film thermal resistance was checked. Finally, Corradini obtained an average heat transfer coefficients for a plate of length L:

$$Nu_{NC} = \frac{K_g}{L} 0.0295 Gr_L^{2/5} Pr^{7/15} \left(1 + 0.494 Pr^{2/3}\right)^{-2/5} \tag{17}$$

$$Sh_{NC} = \frac{K_g}{L} 0.0188 Re_L^{-1/4} Sc^{-2/3} \tag{18}$$

Where NC stands for natural convection, and the Reynolds number depends on the Grashof number through the velocity term.

After Corradini, Kim [16] proposed a more complex formulation that makes use of turbulent diffusivities coupled with a model for a wavy film interface. In this way, the heat transfer is enhanced, which in turn leads to a better agreement with the experiments.

As a conclusion, the mostly of HMT models give a better results than the empirical correlations models. Their most important drawback is the hypothesis of no mass transport toward the exchange surface, although this consideration does not imply erroneous trends in the system response, and can be easily corrected by applying a so-called suction factor. The analogy coupling into a heat transfer modeling based on the diffusion theory of gases to account for noncondensable gas presence in the containment is straightforward and allows a compact presentation of modeling fundamentals.

3. EXPERIMENTAL DATA AND FACILITIES

The main issue concerning condensation on the containment structures phenomenon model validation is the use of appropriate boundary conditions.

Condensation phenomenon depends highly on the scenario conditions, even more when this implies a passive performance, so the conditions are not externally imposed. Moreover, the hardware in question it is very complex because of its dimensions, phenomena, and variable range.

Green and Almenas [11] underlined the fundamental influence of some primary variables over the rate of heat transfer in condensation with noncondensable gases. As these variables show a strong dependency on the boundary conditions, the possibility to scale-up the results taken from separate-effect-tests (SET) is not highly advisable. Specifically, Green and Almenas observed that the thermal resistance of importance was imposed by the gas-vapor boundary layer, while liquid film resistance represented less than 10% of the overall heat transfer resistance, and for typical values of gas concentrations, the fractional resistance gets a maximum of 1% to 2% contribution. From this point the authors suggested a clear parameters division between those which affected to one thermal resistance or to the other. The variables affecting the gas-vapor boundary layer were found to be the pressure, bulk velocity, noncondensables to steam bulk density ratio, and the bulk and wall temperatures difference. All of these variables are scale-dependents: according to the scale, the variable will take a specific values distribution. Moreover, for the velocity there will be not only a scale-dependency on the value, but also on the profile distribution: depending on the scale, there will exist different velocity stream profiles. All this means that for reproducing the real total condensation heat and mass transfer that takes place on the containment structures, it is necessary to account for the primary variables distribution, and this distributions only occur in a large or medium (not SET) facility. This also means that it will possible to validate a condensation model on a SET, but not to extend their results (scale up) to the containment condensation performance. The primary parameters distribution can be viewed in Westinghouse AP-600 PCCS large-scale tests (LSTs) [36].

So the most proper way to validate a condensation on the containment structures phenomenon performance will be that which permits a real containment likewise distribution. This means that not only a large-scale test (LST) will be suitable, but any one as long as is able to reproduce the containment parameters distribution, that is, to be able to reproduce all the relevant non-dimensional numbers in their respective ranges as appeared in the containment.

Lastly, it is also advisable to say that the possibility of validate our studied phenomenon in its dynamic response would require that a heat wall sink exists. For this purpose, a controlled wall temperature would be necessary. The main differences concerning condensation on the containment structures simulation would be the impossibility of checking the dynamic response of our system; it will possible to validate a theoretical model, but not to check the real containment performance.

Next, a review of the main experimental facilities is given. These will include, chiefly, those which were influential both on obtaining empirical models and validating models. Bearing in mind what is outlined above, not all data will be equally useful neither for validate a model nor for develop a model.

3.1. Experimental review

Even though there has been extensive experimental and theoretical research in the area of condensation [25], much less work specifically addressed the condensation process at large scales, such as reactor containments.

The initial experimental database was obtained from separate-effect tests (SET), where bulk velocity was minimized or kept constant. Even when large-scale data was available, usually the atmospheric velocities measurements were not performed.

As it has been said above, it is useful to make a distinction between separate-effect experiments (SET) and integral-effect experiments (IET). The first models that coped with condensation in the presence of noncondensables were derived from SET data. Therefore, these data have been invaluable in the beginnings of the models development, both as a theoretical guide and in the models verification.

Finally, more stress has been made in the experimental programs that have been recently performed, because their knowledge is still not widely spread.

In 1957 Kolflat and Chittenden [37] performed a series of experiments in a stainless steel containment of 22 cubic metres, from which the authors found that heat transfer coefficient was about 620 Btu/(h·ft·°F) (3520.61 W/(m^{2}°C). Subsequent experiments confirmed that this value is not conservative, and probably corresponds to the maximum achieved.

Uchida et al. [6] and Tagami et al. [7] provided some of the pioneering work in this area, which has recently been corroborated by other investigators [8]. This work has led to the development of correlations used in containment safety analysis ([33], [8]) that estimate the Heat Transfer Coefficient HTC based on the ratio of W_{nc}/W_v.

Uchida performed a set of experiments for condensation of mixtures of non-condensable gases (N-C) on the external surface of metal cylinders inside a 45 cubic meters chamber The cylinders were made of brass and copper and had a 0.1 metre radius and a 0.3 meter height. The experiments were carried out in a constant volume vessel initially filled with non-condensable gas at ambient conditions of pressure (1 bar), and temperature (322 K). Steam was supplied to this vessel at increasing mass flow rates in order to obtain increasing total pressures (from one to five bars), while the cooling surface was maintained at constant temperature. Uchida measured the total heat transfer coefficient ($W/m^2\,^oC$) for different values of the N-C to steam bulk density ratio $(\rho_{NC}/\rho_{st})_{bulk}$ and different non-condensable gases, in particular he performed these experiments for nitrogen, air and argon.

Tagami in 1965 reconfirmed Uchida experimental results and later in 1991 Kataoka corroborated the previous results of Uchida and Tagami. Tagami found in the experiments that the heat transfer coefficient increases up to a maximum value that is reached a little before the end of primary depressurization. Later on, the value decreases gradually approaching to the natural convection model value.

Recent experiments [2], and recent theoretical work [38], have been demonstrated that Uchida and Tagami correlations are not suitable because of not considering all the primary importance variables (pressure, bulk velocity, temperatures jump).

Other separate-effect test (SET) data have been obtained by Al-Diwany and Rose [39], who designed a special experiment to remove forced convection effects by means of a flow straightener. Al-Diwany and Rose indicated that noncondensables lighter than steam create an upward flowing boundary layer because when their density become similar to that of vapor Garimella [40] performed a detailed investigation on transient condensation on an aluminum block. The results showed a positive parametric dependency on pressure, and negative on temperatures jump. This work examined the transient nature of the condensation heat transfer process, showing an evidence of the noncondensable accumulation near the interface.

A set of condensation tests on flat plate geometry were performed in Wisconsin University in 1993 [41], the parameters that were varied in the experimental tests included the inlet temperature, the steam mass flow rate and the plate inclination angle from horizontal. The condensing surface of the flat plate was made of aluminum painted with Carbon Zinc II^{TM} to promote the development of condensing films on the surface. The back of the aluminum plate was cooled by oil circulating through coils. The heat transfer rates and the heat transfer coefficient were obtained by measuring the temperature rise and the mass flow rate of the oil coolant flow, and measuring the temperature profile near the condensing surface of the plate. The heat transfer coefficients were obtained at seven locations along the length of the test section.

Another important issue is that with the advent of the new passive containment cooling system designs (PCCS) at the end of the eighties, there has been a change in the potential condensing conditions within the containment. The main consequence of these new designs is that significantly increase the temperature difference between the containment bulk and the wall due to the external cooling in comparison with those of the current nuclear power plants that have no external cooling.

As a consequence of the external cooling of the containment, the absolute temperature of the containment surfaces will be lower, affecting the physical properties like the dynamic viscosity which are relevant to the condensing process.

Westinghouse [36] performed some large scale experiments designed to look at the entire cooling system to evaluate its performance and provide test data for license approval by the NRC. These large scale tests give general information on the pressure, temperature and containment responses in the case of a postulated accident as a function of time, along with some information on the heat transfer rates, but lack some of the insight given by more closely controlled facilities on the effects of both primary and lower order variables.

Some past experiments have been designed to look specifically at these effects at smaller scale. Debhi et al. [42] conducted some experimental work on a 3.5m length and 0.038m diameter tubular geometry with different pressures, mass fractions of vapor-noncondensables, and light noncondensable gases (helium as a hydrogen simulant). This led to the development of correlations that relied on these variables. Despite the valuable information provided by this data the geometry of the facility is a drawback due to the questionable non-uniform conditions in the vessel. Huhtiniemi et. al. [41] considered the effects of orientation and bulk velocity in a smaller rectangular facility. He improved on the cooling design of Debhi; however, the small size required him to impose a forced velocity flow parallel to the cold wall so that he could achieve velocities similar to those anticipated in an actual containment accident.

To bridge the gap between the large time varying simulation of an accident (Westinghouse) and the smaller separate effects studies (Debhi, Huhtiniemi), an experimental program which addressed conditions similar to those expected during an accident in the AP600, at an in-depth level was conducted [2]. Specifically, this experimental program was aimed at achieving a thorough understanding of the role of both major and minor variables on the heat transfer rate, along with providing a valuable data base to validate heat transfer models. A thorough description of the facilities and the experimental techniques used was given by Anderson et al. [2]. Two experimental facilities were constructed with similar features to the actual reactor such as a proper aspect ratio, similar surface finishes, and the ability to achieve prototypical accident conditions. Qualified experimental results were gathered by demonstrating test reproducibility and by using redundant and accurate measurement techniques for the HTC. Particular care was taken to follow a representative test protocol that allows an experimental test matrix of over 70 tests to span the expected range of conditions. Molar fractions of noncondensables-vapor ranged from 0.4 to 4.0, and helium concentrations in the noncondensables mixture were from 0% to 50% by volume. All the primary variables, including also noncondensables composition and the inclination of the condensing surface, were studied and measured. Some of the conclusions of the experimental work were that at inclinations more than 5° from the horizontal, the heat transfer is enhanced due to the break up of the continuous quiescent film into a rippled structure due to rolling and coalescence of droplets. Anderson also observed the great influence of the temperatures jump over the heat transfer rate, as well as the influence of pressure (over all, due to the increasing in the vapor-noncondensables relation).

The experimental series of the CVTR (Carolinas-Virginia Tube Reactor), carried out in 1969 [43], provided some design-basis accident (DBA) information (according to many authors, their results constitute the most reliable empirical data relating heat transfer coefficient). These series consisted of a superheating vapor injection for 180 seconds in a 6424 cubic meters vessel (1:10 of dry containment PWR). Heat transfer coefficient values were low at the beginning of the injection, but later they experimented a sudden increase up to a maximum just before the end of the injection supply. Later on, a fast decrease took place as turbulence decreased. Some stratification was observed at high levels of the volume due to the lower vapor density, which caused the larger heat transfer coefficient (always lower than 1500 $W/(m^{2o}C)$).

Another full-scale facility is the realistic full-height German Heissdampfreaktor HDR [44-45]. The HDR containment facility is an actual decommissioned containment with a volume of 11060 cubic meters, and a height of 60 metres (as actual containments). The tests carried out in the facility covers a wide spectrum of simulated accidents conditions. The amount of vapor emitted in these tests was scaled by volume and included not only the steam available from the primary system but the steam generated during tens of hours owing to the decay heat. The facility has over 700 data channel measurements, among them, 23 heat transfer blocks used to measure surface heat fluxes over the entire volume, where different vapor-to-gas concentration ratios and different levels of atmospheric turbulence (including velocity measurements) existed.

Other important large-scale tests are those of Battelle-Frankfurt [46] and the well known Marviken experimental facility containment tests [47]. The Battelle Frankfurt Containment (BFC) test facility in Germany is a 1:5 scale model concrete containment with a total free volume of about 580 cubic metres. The containment model has several compartment configurations. In the facility gas concentration, gas temperature, structure temperature, heat transfer, and velocity have been measured. Several tests have been carried out, including the injection of soluble aerosol into wet atmosphere, injection of mix aerosol with hydrogen burn, and steam and air injection (in some test including Helium).

The main problem with CVTR, HDR, BTC and Marviken facilities is that they do not have a controlled wall temperature, so the temporal evolution containment performance will not be able to be simulated.

Another important experimental exercise was performed under the International Standard Problem ISP-47 [48], which has the objective of demonstrate the actual capability of CFD and 'lumped parameter' codes in the field of containment thermal-hydraulics. To reach this objective, a two-step strategy was proposed: in the first step, the validation of refined models in the separate effect facility TOSQAN (7 m^3) [49] and at larger scale in MISTRA (100 m^3) [50] would be carried out, and in the second one the validation of codes would be addressed in a complex and more realistic compartmented geometry ThAI (60 m^3) [51].

The idea of the TOSQAN project is to perform an intermediate study between separate-effect tests and integral tests, considering three phenomena (plume/jet flows, condensation on walls and natural convection), with a high density of instrumentation. The TOSQAN enclosure is a cylindrical chamber of stainless steel and a sump. The total internal volume (including the sump) is 7.0 m^3. It is of relative small size with well-controlled wall temperature, making realistic CFD improvements with actual computer power. It is well instrumented with great possibilities of non-intrusive measurements. The TOSQAN facility is mainly used for the validation of 'elementary' phenomena (condensation, spray systems, sump-atmosphere interaction), so that it is not designed to represent a real reactor at a smaller scale. The pressure range was from 1 to 6 bar, with 15% to 75% gas mass fraction and gas mean temperatures from 60º C to 153º C. The main results concerning heat and mass transfer are the followings [52]:

1. They have distinguished four zones in the facility by means of a numerical calculation using TONUS 3D code: the injection zone, the recirculation zone (connected with the injection zone), the condensing region and the natural convective flow occurring below the injection. They have focused their attention on the condensation and bulk region.

2. It has been carried out heat transfer coefficient comparisons with Uchida, Tagami, Kataoka and Dehbi correlations. An exhaustive work has also been developed in the mass transfer field. It has been compared different mass flux formulations (Chilton-Bird, Collier-Stephan, Chilton-Bird enhanced) with the experimental measurements. It has also been studied different formulations of mass flow rates, that is to say, from a specific mass flux formulation, which is the weight of the empirical correlations need for close the mass flow rate formulation (Sherwood correlations, Diffusion coefficients).

3. A study of guessed secondary contributions has been made, more precisely, radiation and convection heat transfer rates, being confirmed the present suppositions. Moreover, in order to study the possibility of neglecting the liquid film thermal resistance, interface temperature has also been calculated from Uchida correlation (liquid film resistance model being already computed). The results showed an interface to wall maximum difference of 0.4º C. Although this is a small value, since condensing wall temperature is of major influence on the level of pressure in the containment, a small variation of this value (and therefore on interface temperature value) can have an impact.

Related with MISTRA facility, two tests have been carried out dealing with condensation walls in the presence of noncondensables [53]. In the first of them, "Superheated steam injection and condensation MISTRA M2 and M3 tests, effect of injection location for 3D full validation", steady states are reached for centred (M2 test) and for off-centred (M3 test) jets of superheated steam, and the results of pressure, condensation mass flow rate, steam and velocity axial concentration profile, and thermal field have been compared with TONUS 3D code results [54]. The second test, as it has been said above, is the first step of ISP 47 benchmark, where pressure, mean temperature and mean steam concentrations were compared with lumped-parameter code results. For CFD codes they also include local data like temperature, steam concentrations and radial profiles of the 3D velocity fields.

ThAI facility is a 60-m^3 stainless steel vessel, 9.2 m high and 3.2 m in diameter. It can be operated up to 180°C and 1.4 MPa overpressure, the latter value allowing also performance of hydrogen experiments. Conventional instrumentation is provided for pressure (measuring accuracy ±15 mbar), fluid and structure temperature (±0.3 K), feed mass flow (± 1.6 % of full range), wall heating/cooling power, water level (± 2.5 mm), condensate mass measurements, 10-channel sampling system for continuous gas (He, H2) concentration monitoring (±0.2 vol% referred to the non-condensable gas+air fraction), and by six new-developed sensors for dew-point temperature (±0.5 K) designed for measurements under near-to-saturation conditions up to 140°C. In Part 1 of the ThAI project (1988 – 2003) the test facility has been built and a total of 10 thermal-hydraulic and 8 iodine experiments have been performed. These experiments involved natural convection effects, some also stratified atmospheres with subsequent dissolution of the stratification by external measures, at both superheated and saturated test conditions. In ThAI Part 2 (2003 – 2007) [55] the experiments are continued with a variety of further topics in the fields of thermal hydraulics, iodine, aerosols, and hydrogen. Unfortunately, to date the author of this work has only found results from iodine experiments.

The Nuclear Power Institute of China (NPIC) has developed some preliminary experiment research and relative theoretical analysis for passive characteristics of advanced PWR nuclear power plant AC600/1000 [56]. This experiment research plan has been divided into three steps. In the third step, NPIC has constructed (or is nearly constructed) an integral containment cooling test facility in order to simulate and research comprehensive characteristics of passive containment cooling system for AC600/1000. In the first two steps, it has been studied the secondary side of the containment passive safety system, i.e., the natural circulation characteristics of air in the annular channel between the steel shell and the concrete shell of the containment. In the first-step study (the second one is not completed), the air flow resistance characteristic and effects of air channel shape and air location on natural circulation flow have been studied, as well the influence of environment wind and surrounding buildings, and the velocity field and surface wind pressure distribution of containment. The facility is 1:10 in scale. The results showed the existence of an enclosed vortex in the stagnant bottom and a separate bubble formed at the rear of the baffle, and also a positive pressure when the angle is between -35º and 35º. The test results also revealed that the natural convection flow rate was enhanced in general by outside wind, and horizontal wind has a better effect than other one. Lastly, the natural convection is affected by the position of chimney. The distance between this one and the containment must be at least four times the chimney diameter (however, in any test hot air recirculation occurred).

Another experiment related with the secondary side of the PCCS is the one carried out by Kang and Park [57]. In their work, they concluded that both water temperature and air mass flow rate had strong (positive) effects on the heat transfer rate, while the water flow rate has only little effect. With respect the gap size, the heat transfer coefficient reduces as the channel width increases. The evaporative heat transfer coefficient were experimentally obtained in a vertical duct with one-sided heated plate under counter-current conditions of forced convective air and a free falling water film. The test channel consisted of 2 metres length, 0.5 wide and 10 mm thick stainless steel plate. The experiments were performed under varied conditions of air flow-rates, film flow rates, film temperatures and with different gap sizes.

It was also obtained an empirical correlation for the Sherwood number -thus the evaporative mass flux.

Another recent experimental program has carried under the joint research project of DABASCO (acronym for common experimental Data Base for Development of physical models and correlations for thermal-hydraulic Containment analysis) [58], which is supported by the European Community under a cost-shared contract and participated by nine European institutions. The project consists of seven separate-effects experimental programs, which deal with new innovative conceptual features. The DABASCO project deals with several important phenomena involved in the containment thermal-hydraulic analysis, among others, with the influence of non-condensable gases on condensation. One of the carried out program was the COPAIN separate-effect test (SET). The general aim of the COPAIN work package at CEA, Grenoble, is to investigate steam condensation on vertical walls in the presence of noncondensables gases. Several parameters have been studied (pressure (0.12, 0.4, 0.66 MPa), temperature, heat flux, gas composition (0% to 100% of gas mass fraction), gas velocity (0.1 m/s to 3.0 m/s)). The test section consists of a vertical condensing plate of height 2 m and width 0.6 m which is located in a rectangular channel of depth 0.5 m. The facility is provided with a water cooler which permits to control the wall temperature. During experiments, the heat flux through the plate (at 20 locations), liquid film thickness (at four locations), gas temperature, gas velocity and vapor-gas mixture composition haven been measured. In order to interpret the results, prepare and analyze the tests, the HMT analogy has been used. In this way, they have studied the influences of the gas velocity over the heat and mass transfer coefficient, running different tests varying the gas velocity from forced to natural convection. They have concluded that the used Dittus-Boelter correlation , in terms of Nusselt number, depends on the Reynolds number (with a power of 0.8) as long as velocity is higher than 1 m/s. When velocity is 0.5 m/s or even lower, this correlation breaks up and the buoyancy forces start prevailing. The same occurred with the Sherwood number. Finally, a new correlation for the Sherwood number has been derived.

The NUPEC (Nuclear Power Engineering Corporation) facility consists of a ¼ linear scaled PWR dry steel containment, which has a free volume of 1300 cubic meters [59]. This containment mock-up has 25 inner compartments reflecting an actual plant layout. The facility consists of a cylindrical wall with a hemispherical dome at the upper part, the dimensions are: 17.4 m high, 10.8 m of diameter. A gas supply system for steam and helium (used as a safe hydrogen simulant to avoid explosions during the experiments) is provided with the facility. It can be measured the gas (helium) concentration (29 points), the gas temperature (34 points), the structure temperature (146 points), and the gas velocity (10 points). The NUPEC facility represents a multi-compartment containment. It includes the main rooms of any actual 4-Loop PWR plant, but excluding metallic components such as Steam Generators, pumps, etc. Two tests have been performed without activating the sprays.

The PHEBUS-FP program [60] is performed by the French IPSN together with contributions of the CEC, EDF, Japan, Korea, and USA. This program has been mainly designed to obtain experimental reference data to check and qualify the code systems used in the safety analysis of source term evaluation. The containment houses a 10 m^3 volume. It consists of a 4.5 m high and 1.8 m diameter cylinder closed at top and bottom by ellipsoidal surfaces. The floor of the vessel is equipped with a 0.5 m depth and 0.528 m diameter sump, respect to a representative PWR containment one. To achieve a representative ratio, the internal facing surfaces of the vessel were “neutralized” by heating them up to a thermal state slightly over the one of the containment atmosphere. Three cylindrical structures (2.6 m high, 0.15 m diameter) were attached to containment ceiling to provide a total surface area of around 2.3 m^2 for heat transfer. . Each of them was divided in two parts: an upper one called “wet” or cold zone (0.775 m^2), designed to control steam condensation; a lower part called “dry” or hot zone (0.336 m^2) where sliding condensate from the wet section is collected and then drained to the sump. On the condensing surface, the temperature can be controlled by the use of an organic liquid coolant system inside the cylinder. This system regulates the condenser surface temperature and maintains it to an almost uniform temperature for all condensing surfaces. They are instrumented with level sensors that measure condensed mass. The containment instrumentation measure H2 and O2 concentrations (1 point), gas temperature (25 points), sump temperature (4 points), structure temperatures and condensation rates. The condensation flow rate is deduced from the information given by the level sensors located inside the water collection bottles, which are periodically emptied by returning the collected water to the sump.

4. CONTAINMENT CODES

The reason why containment modeling has to deal with particular codes is because of its unique dimensions. Furthermore, when we are talking about passive performance of the containment safety systems, the codes have to be capable of simulate all the natural circulation specific phenomena (buoyancy forces, thermal and concentration stratifications, condensation and evaporation, mass diffusion, etc.), together with the appropriated system boundary conditions (liquid evaporative film in the PCCS secondary side, air flow in the annular channel between the steel shell and the concrete shell of the containment, etc.).

The capacity to reproduce the Condensation on the Containment Structures greatly depends on how this phenomenon has been defined. What was said about the available experimental data has to be applied for the phenomenon modeling: although a separate-effect test (SET) is able enough to validate a theoretical model over the range covered by the test, if the phenomenon encompasses its performance in the containment, strictly speaking, the only way to validate an implemented model in a code would be through an experimental facility able to reproduce the containment parameters distribution. Most of the condensation models implemented in codes have been validated through a separate-effect test (SET). Some other codes, on the other hand, have been validated through large-scale tests (LST) (GOTHIC, COMMIX-1D). Furthermore, it would be advisable to make another distinction among those validated in large facilities (CVTR, HDR), and those which have been compared with facilities that are able to reproduce the passive containment cooling system (PCCS) (Westinghouse large-scale tests, MITRA).

Many codes have implemented Uchida and Tagami correlations. The large uncertainties over the turbulent degree in the atmosphere containment, the ignorance about the structure characteristics, and the difficulty of applying local heat transfer coefficients to the large surfaces of the containment, caused that instead of using a Nusselt modified theory to deal with condensation heat transfer coefficient, empirical correlations were implemented. The conservative approach of Uchida and Tagami correlations in CVTR tests, and their qualitative coincidence with the observed tendencies, were important issues to prefer this kind of models than Nusselt's based models. As a consequence, many of the current codes still use Tagami and Uchida correlations, although the implementation algorithm is not always the same.

Next, some of the main containment codes will be overviewed. For each code, a first general description will be followed by the specific condensation models implemented in the code. When possible, recent comparisons with experimental data will be depicted.

GOTHIC (Generation Of Thermal-Hydraulic Information In Containment) [61] is a general purpose thermal-hydraulics code that has been successfully used by several utilities to resolve key technical aspects in the areas of equipment qualification, accident analysis in support of probabilistic risk assessment, high energy line break analysis, room heat up calculations, technical specification changes and other areas. The code has many of the modeling capabilities needed to analyze the thermal-hydraulic response of the new passive containment designs as well as currently operating designs. GOTHIC can model buoyancy-dominated flow, condensation and evaporative heat transfer in the presence of noncondensables, and stratification. GOTHIC solves mass, momentum and energy balances for three separate phases: vapor, continuous liquid (pools, films, etc.) and dispersed liquid (drops). The vapor phase can be a mixture of steam and non-condensing gases. A flexible noding structure allows the use of a variety of noding arrangements to accommodate the wide range of containment modeling needs. Containment compartments can be modeled using one-, two- or three-dimensional rectangular grids. Many containment problems cover long periods of real time so that finely noded multidimensional models are impractical. For these problems a simpler lumped parameter analysis may be used. Wall heat transfer correlations are incorporated for a wide range of heat transfer situations, including condensation heat transfer in the presence of non-condensable gases. Multiple effects tests from HDR [44], LACE [77], Battelle Model Containment [46], Marviken [47], and CVTR [43] have been modelled with generally good to excellent agreement with the test data. For solid structures, GOTHIC employs heat transfer correlations that account for the effects of condensing steam and the non-condensing gases that build up in the boundary layer, reducing the rate of condensation. The condensation options in GOTHIC include the empirical Uchida (1965) correlation and the semiempirical correlation developed by Gido and Koestel based on boundary layer theory with certain coefficients adjusted to give good agreement with experimental data including those obtained by Uchida. There are two parts to the G-K correlation, one for the free convection regime and one for the forced convection regime. A third option in GOTHIC is to use the maximum of the values calculated from these correlations. Moreover, to be able to perform the containment DBA analyses for the Westinghouse AP600 Advanced Plant containment, special subroutines were developed and added to the code to model heat and mass transfer to and from evaporating and condensing films. The resulting code version, WGOTHIC, was approved by the NRC to perform the containment DBA analyses for the AP600. Kennedy et al. [5] studied the thermal performance of PCCS for a heavy water reactor facility following a DBA using a 1:10 scaled down test vessel. The WGOTHIC code was used in the analysis. It can be said that GOTHIC has the models necessary to simulate containment systems and has been verified for a range of phenomena deemed essential to passive heat rejection from containment. GOTHIC code has been extensively validated with many facility tests. Among others: BFMC blowdown tests D-1, 15 and 16, C-13 and 15, HEDL hydrogen mixing tests HM-5 and 6, Marvikken tests 17, 19, 22 and 24; CVTR DBA tests 3, 4 and 5; and HDR tests V21.1, T31.1, T31.5 and V44. This validation database has recently been extended by Battelle's application of GOTHIC to the CEC-F2 experiment, VANAM-M2, PAR test MC1 and MC3, all in the Battelle Model Containment (BMC), and several 225 HDR tests, including simulations of E11.2 and E11.4 using a truly two-dimensional six-node region for the dome [62].

Sha [63] also took the same large-scale tests (LST) but using COMMIX-1D code [22], which is a single-phase flow with multicomponents. To simulate the PCCS performance of the AP600, Sha divided the containment model into three domains, namely a bulk gaseous mixture inside the containment vessel is denoted as domain 1, bulk moist air in an annulus between the outside containment shell and the inside shielding building wall is denoted as domain 2 and a thermal coupling domain linking domains 1 and 2 is named as domain 3. The thermal coupling domain consists of condensate film inside the containment vessel wall, the containment vessel wall itself, evaporating liquid film outside the containment vessel wall, and paint on both sides of the vessel wall. COMMIX-1D code solves mass, momentum and energy equations for a mixture of N components, based on the porous-medium formulation through local volume averaging (Sha et al., 1981). In the analytical model, it is assumed that: the volume occupied by the thin liquid film in domain 1 or 2 is very small relative to the corresponding volume of domain 1 or 2 and can be neglected without affecting overall results, and both the evaporation and condensation rate at the interface between the liquid film and the bulk gaseous mixture can be computed iteratively and treated as boundary conditions for domains 1 and 2. For the closure relations, it is used the transport equations for $k-\varepsilon$ two-equation turbulence model, Turbulent transport properties, and a liquid-film tracking model, both for the condensate and evaporative film. The liquid films are considered in the thermal coupling between flow domains inside and outside the containment vessel. The tracking models compute the liquid-film thickness, its mean velocity and temperature on both sides of the steel containment vessel. The local convective heat transfer coefficients, as well the mass transfer rate and coefficients, are obtained from CONTAIN code [64] models, that is, Collier's model.

PCCSAC-2D, 3D, [65] are special two and three dimension computer codes developed by the Nuclear Power Institute of China (NPIC). PCCAC-2D is a two dimension computer code already used in the design of AC600/1000 passive containment cooling system. PCCAC-3D is a three dimension computer code finished in September 2000. Both codes can predict pressure and temperature of mixing gas inside the containment in a design-basis-accident (DBA). The heat removal characteristics from inside containment to atmosphere through the water film on the out surface of steel shell and natural circulation flow of air can be also simulated in the codes. The general structure of the code, together with the implemented condensation model, is very similar to COMMIX-1D code. The condensation model uses Collier's formulation both in the condensate mass flux and in the mass transfer coefficient correlation. The results have also been compared with those obtained in the Westinghouse's 1/8 scale test facility for AP600 large-scale tests (LST) [5], giving a good agreement with them.

CFX results have been compared with TOSQAN thermal-hydraulic tests results [66]. CFX is a Computational Fluid Dynamics (CFD) code [67]. CFD codes solve the mass, momentum and energy transport equations when a fluid system is modeled using local instantaneous description. As modeling of condensation is not yet commonly included in CFD codes, this has to be implemented by the code user. Two kinds of approach are currently being used to model condensation. The first approach is modeling based on first principles: heat and mass transfer on condensation surfaces are rigorously derived from first principles. Although this approach will probably prevail in the future, its main drawback at present is that a very fine computational grid is necessary near the condensation surface, which causes long computation times. The second approach is to include heat or mass transfer empirical correlations, and apply them in the layer of cells contiguous to the condensation surface. In these correlations, some physical variables pertaining to the bulk flow usually appear. One of the problems is the choice of appropriate values of the bulk flow parameters from the computational grid used by the CFD code. If values from the cells contiguous to the condensation surface are applied, then relatively large cells must be used, which may not be adequate for modeling of other phenomena, as the fluid flow, or the concentration gradient of the gas-vapor components. The essential discrepancy is that CFD codes were developed to solve equations that are derived from first principles, using local instantaneous description, whereas the empirical correlations are function of average physical properties. Calculated temperatures, species concentrations and vertical velocities during three steady states were compared to experimental measurements. Despite some discrepancies, the general agreement between experimental and calculated results shows that the proposed approach is adequate and could be applied to similar simulations. The problem is that, despite significant advances in computational power, the CFD-type mesh detail is still impractical for containment modeling (besides the mentioned problem above, about the significant modifications and verifications of code logic that have to be done before CFD-type codes can adequately simulate the gamut of phenomena important in a passively-cooled containment. CFX-4 has been also validated with NUPEC facility [59] where, again, a condensation model has been implemented. This model is based on Nusselt condensate film theory, and a degradation factor developed by Terasaka, which is a polynomial correlation function of the noncondensables mass fraction. Good agreements were found with the experimental data.

FLUENT code [68] has also been validated with the phase A of the TOSQAN test [69]. In this case, as the code has not a condensation model either as CFX code, it has been necessary to modify it. Instead of taking the empirical correlation approach (as it was with CFX code latter case), this time the followed method has been similar to what Sha carried out in COMMIX-1D [63], that is, to consider one gas phase and modify the heat and mass sinks to include the effect of the condensation. The work conclusions stated that the pressurization transient was successfully performed; the CFD model predicts very accurately the pressure time trend; a lower performance is obtained in the prediction of the mean temperature time trend, due to the differences in the averaging process and in the involved thermal capacities of the experimental apparatus (the experimental mean temperature is obtained as an average of the values of the measured temperatures, so coming from the 42 thermocouples present inside the TOSQAN vessel; instead, the calculated mean temperature is obtained as an average of the local temperature over all the vessel volume); the good behaviour of the CFD code is also confirmed by the comparison of the radial and the axial calculated profiles of the atmosphere temperature, steam concentration and axial velocity, obtaining a valuable prediction of the flow conditions inside the TOSQAN vessel not only in the steady-state periods but also during the transient phases.

The Modular Accident Analysis Program (MAAP) code [70] was initially developed as an integral system model to represent the response of the reactor core, the Reactor Coolant System (RCS) and containment to a set of conditions that could result in damage of the reactor core. Included in the original development scope were Boiling Water Reactors (BWRs) and Pressurized Water Reactors (PWRs), combined with the Mark I, Mark II and Mark III containments for BWRs, includes best estimate evaluations of the containment response as well as a model that follows formulations in the NRC Standard Review Plant (SRP). In this regard, the best estimate containment model includes representations for forced convection throughout the containment that are induced by the momentum of the blowdown break discharge flow. The licensing basis version (MAAP-DBA) represents the energy transfer to the passive heat sinks in terms of more conservative evaluations for the energy transfer rate, for example those initially formulated by Tagami and Uchida. The two model code results (best estimate and conservative approach) have been recently compared with two CVTR tests [71]. The MAAP-DBA model overstates the containment pressurization for both tests and also overstates the peak temperature in containment, whereas the peak pressures and temperatures are well represented by the best estimate model.

The Containment transient analysis tool for PWRs or BWRs (CONTAIN) has the capability to model thermal-hydraulic phenomena (within a lumped-parameter framework) for existing containment designs. This code is the NRC's best-estimate tool for analyzing accident scenarios. CONTAIN uses the heat and mass transfer analogy (the so-called Collier correlation, that is a heat transfer formulation based on Collier's work) for modeling condensation phenomenon. The code can choose between forced and natural convection correlations (by taking the largest predicted Nusselt number). CONTAIN code uses a mechanistic approach based in the vapor diffusion theory in the presence of noncondensables. In the implemented model, the liquid thermal resistance is neglected, so the interfacial temperature is equal to the wall temperature.

CONTEMPT-LT [72] was developed to predict the long-term behaviour of water-cooled nuclear reactor containment systems subjected to postulated loss-of-coolant accident (LOCA) conditions. CONTEMPT-LT calculates the time variation of compartment pressures, temperatures, mass and energy inventories, heat structure temperature distributions, and energy exchange with adjacent compartments. CONTEMPT-LT computes condensation in the presence of noncondensables model based on the vapor diffusion theory, using Collier's correlation. This model is almost the same as the one implemented in CONTAIN 1.12 code. CONTEMPT-LT also considers the interface temperature as the wall temperature.

CONTEMPT-4/MOD5 [73] describes the response of multicompartment containment systems subjected to postulated loss-of-coolant accident (LOCA) conditions. The program can accommodate both pressurized water reactor (PWR) and boiling water reactor (BWR) containment systems. Also, both design basis accident (DBA) and degraded core type LOCA conditions can be analyzed. The program calculates the time variation of compartment pressures, temperatures, and mass and energy inventories due to intercompartment mass and energy exchange taking into account user-supplied descriptions of compartments, intercompartment junction flow areas, LOCA source terms, and user-selected problem features. CONTEMPT-4/MOD5 arranges the heat transfer coefficients in a table according to the noncondensables and vapor mass fraction ratio: depending on the ratio value, the code will compute whether Tagami correlation or a different one. Recently, CONTEMPT4/MOD5 has been used to model the PCCS of the AP600 [57]. The problem was that the code could not correctly simulate it, because of the absence of appropriated boundary conditions for the outside part of the containment (PCCS annulus heat transfer), so heat transfer correlations were introduced. Unfortunately, the authors did not mentioned neither the experimental data based used to validate the model, nor the calculated results.

The MELCOR code, developed by Sandia National Laboratories (SNL) by charge of the Nuclear Regulatory Commission at the USA (US-NRC) [74], is a lumped-parameter code able to simulate the progression of severe accident both in Pressurised and Boiling Water Reactors. The list of phenomena now covered by MELCOR models includes two-phase hydrodynamics, heat, and mass transfer, both in the reactor and in the containment; decay heat generation; fission-product release and transport (including relocation of heat sources); aerosol physics; core and lower plenum thermal response, degradation, and relocation; gas combustion; thermo-mechanical response of the vessel lower head; low- and high-pressure melt–ejection phenomena; and melt–concrete interactions. In addition, models are included for control systems and engineered safeguards. MELCOR uses a control volume/flow path calculation method. The MELCOR Co-operative Assessment Program (MCAP) is an ongoing activity to assess the code against experiments and in performing plant analyses [77]. Currently most major experiments are or have been modelled with MELCOR by the code developers or users of MELCOR. Among others: Marviken-V [47], BMC [46], HDR [45], NUPEC hydrogen tests [59], PHEBUS (FP and SFD) [60], GE Large Vessel Swell, etc. Regarding condensation model, this is similar to CONTAIN, so it is based on the heat and mass transfer analogy using the correlation of Chilton-Colburn; for the mass flux, MELCOR is based on Collier's formulation. MELCOR has been recently validated with NUPEC facility test [59], and it has found that the MELCOR model needed a calibration with a multiplicative constant (×10) in the mass transfer coefficient to fit good results. MELCOR has also been recently validated with TOSQAN and MISTRA facility under the ISP-47 exercise [75]. Regarding TOSQAN small-scale facility, mean pressure and temperature have been compared, having an excellent agreement for the steady-state values, while some discrepancies appear in the transient states However, the updated MISTRA model did not shown the same agreement between predicted and measured steady state total pressures. This seems to be apparently because of the multidimensional phenomena taking place in the large-scale test.

The COMPACT lumped-parameter code [76] was originally developed by Westinghouse Electric Corporation for BWR and PWR severe accident analysis with the aim of providing fast, economical computation of the long-term conditions in multi-volume geometries. A program of joint development was undertaken by Westinghouse and NNC to improve the modelling of various phenomena. With respect to condensation models, the code uses the Tagami correlation for blowdown areas, while uses Uchida correlation for the rest of the containment. COMPACT has been validated with a NUPEC facility test [59], and good agreements have been found.

The TONUS code, developed by the French IPSN [49], combines the multicompartment approach with the multidimensional approach. It solves the Navier–Stokes equations with a turbulence model. Near the walls, the mesh has to allow the description of the boundary layer, or adequate empirical correlations have to be developed to calculate velocity of the flow and heat transfer between gas and structure. The level of model detail for physical phenomena is defined by the global accuracy required. In this way, the code is said to be able to be a field code and a lumped-parameter code. The user has access to a programming language to enter his choice for physical models from existing ones, introduce new physical models, implement geometrical meshes adapted to postprocessing of data, and choose a numerical solver. The user is able to generate heat and mass sources at any location for any period of time. The code has been validated in MISTRA [50], COPAIN [58], and TOSQAN [49], where velocity field, local temperatures, and gas concentrations have been compared with a good agreement.

The containment code system COCOSYS [56] has been developed for the comprehensive simulation of severe accidents in light-water reactor containments. It can simulate all relevant phenomena, processes and conditions that may occur inside the containment during such accidents. COCOSYS is also able to simulate design basis accidents. The COCOSYS system is divided into three main modules for thermal-hydraulics, fission products and aerosols, and melt behavior. General CFD-codes can be externally connected (as if another module) with the internal COCOSYS part. COCOSYS thermal-hydraulics has been validated among others, in BMC, HDR, and NUPEC facilities.

As it has been shown, there are a great number of codes that can model the containment and analyze its response. Among them, it can be said that:

1. The commercial 3D codes, like CFX, FLUENT, or GASFLOW, have still not the possibility of modeling condensation if an appropriated model is not implemented by the user. What can be stated is that their capabilities to represent the main thermodynamic variables of the containment in their spatial and temporal distribution have been demonstrated.

2. The condensation models of the lumped-parameter codes are based whether on empirical correlations or on heat and mass transfer analogy. Both methods have been validated extensively using many experiments, including large scale tests. The ISP-47 [48] exercise results showed that all lumped-parameter models calculate similar heat transfer coefficients with a spread of 30%. Based on overall indicators such as the measured system pressure and total measured condensate masses -as it is the case of MELCOR validation with TOSQAN-, and on local indicators for a Westinghouse AP600 large-scale tests in GOTHIC validation-, it can be concluded that the total condensation can be predicted quite well using lumped-parameter codes.

3. Regarding field codes, as empirical correlations are based on fully developed flow conditions and are formulated in terms of mean flow quantities, whereas local quantities are computed in this kind of codes, therefore, it can be difficult to apply empirical correlations correctly in this type of code. Usually, the liquid volume is neglected without affecting overall results, being the condensation rate treated as a heat and mass sink (like a boundary condition for the bulk gaseous mixture, so coupling in this way the balance equations. As the difference between the interface and wall temperature are usually small (lower than 1º C [52]), both temperatures are set to equal in many codes.

4. There are still many nuclear codes that have implemented an empirical correlation. As it was said above, this kind of models usually can deal only with a specific range of boundary conditions, whereas the containment thermodynamic scenario is largely heterogeneous, apart from not considering all the primary variables affecting the condensation on the containment. For this reason, their implementation is not recommended.

5. The trend in nuclear containment codes, as it can be seen in more recent codes as TONUS or COMMIX-1D, seems to be inclined to the use of codes -both lumped-parameter or field codes- where a heat and mass transfer analogy condensation model is used, instead of an empirical-correlation based model.

Following the classifications made either in the codes chapter, as well as in the models chapter, a general code classification has been made in order to clarify the codes depending on its original purpose, the type of containment model, and the implemented condensation model. Regarding experiments, it would be hard to know the extent of each code validation.

The classification will be a matrix where the row entrances will be the codes, and the column entrances will stand for different features of the code.

Regarding the objective of the code, it is possible to differentiate between a code not exclusively developed for the nuclear field, and a nuclear code. The main difference among them is that the latter has been widely validated with containment-simulated facilities.

Regarding the nature of the code, we can differentiate between lumped-parameter codes and field codes, which can model all the conservation equations in a multidimensional way, so avoiding both the use of a one-dimensional momentum equation form between two connected volumes, and the restriction of not considering the spatial differences of thermal-hydraulic values inside a control volume. Even this, several codes start being *at the middle* in this classification, in the sense that have some features from both groups. This is the case for TONUS code, which is a lumped-parameter multidimensional code (it solves de Navier-Stockes equations with turbulence modeling over a number of meshes), or GOTHIC, which has the possibility of modeling the containment compartments using a three-dimensional rectangular grid.

With respect to the condensation model, the classification of the models chapter will be followed. So the code can have whether an empirical model, a field approach model, or a model that makes use of the heat and mass transfer analogy. In the first and the latter case, the specific implemented model will be stated.

Code	Type of code	Nature of the code	Condensation model
GOTHIC	Nuclear	Lumped-parameter	Uchida correlation and Gido and Koestel correlation
COMMIX-1D	Nuclear	Field code	Collier's model (HMT)
PCCSAC	Nuclear	Field code	Collier's model (HMT)
CFX	Commercial	Field code	No implemented
FLUENT	Commercial	Field code	No implemented
MAAP-DBA	Nuclear	Lumped-parameter	Uchida and Tagami correlations
CONTAIN	Nuclear	Lumped-parameter	Collier's model (HMT)
CONTEMPT-LT	Nuclear	Lumped-parameter	Collier's model (HMT)
CONTEMPT-4/MOD5	Nuclear	Lumped-parameter	Tagami correlation and others
MELCOR	Nuclear	Lumped-parameter	Collier's mass flux and Chilton-Colburn correlation (HMT)
COMPACT	Nuclear	Lumped-parameter	Uchida and Tagami correlations
COCOSYS	Nuclear	Lumped-parameter	
TONUS	Nuclear	Field code	

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