Studies dealing with defogging and de-icing phenomena on vehicles’ windshield: a review

A Ene, C Teodosiu
STHPA department, Faculty of Building Services, Technical University of Civil Engineering Bucharest, Romania

Corresponding author: alexandra.angelescu@phd.utcb.com

Abstract. The condensation process represents the phase change phenomenon through which the water vapours from air are transformed into liquid together with heat release. The phenomenon can take place either in the bulk of the fluid and it’s named homogeneous condensation, or it can appear on a solid surface and it is heterogeneous condensation. This paper proposes to provide an insight into the condensation phenomenon through the lens of experimental and numerical approach in different configurations. The focus is set on the condensation/evaporation process inside vehicles’ cabin as the evolution towards electric vehicles is starting to make a mark on the industry. The paper presents the impact of the HVAC system on both, energy consumptions and driving security. As the electric vehicles are prone to a general driving range of around 200 km depending on the battery systems, this driving range can be significantly reduced up to 40% by the usage of the HVAC system [1]. Therefore, the methods for reducing and maintaining the condensation phenomenon away from the glazing surfaces of the vehicles’ cabin, especially on the windshield are going to be tackled in order to provide a general view of the actual state of this subject.

1. Introduction

Since the industrial revolution begun, the global level pollution has been rising constantly, on one hand, due to novel technologies that had replaced the manual work, while on the other, due to the growth of the indoor environmental comfort. Therefore, people have started to make use more of the fossil fuels. Together with new means of transportation, new technologies appeared in order to maintain a healthy and comfortable indoor environment, leading towards a growing concern of reducing the energy consumption. In 2007, the fossil fuels were used in a proportion of 95% as main resource for personal vehicle transportation, representing at the same time 50% of the total fossil fuels consumptions [2]. In addition, in 2017, the primary energy production is maintained based on 87.6% on fossil fuels [3]. Furthermore, in 2016 personal vehicle transportation was responsible for more than 44% of the greenhouse gas (GHG) emissions in Europe from the ones produced by transportation. Therefore, reducing the energy consumption and GHG must be tackled as soon as possible [4]. The evolution from Internal Combustion Engine Vehicles (ICEV) towards Electric Vehicles (EV) seems to represent the main reason why researches should focus more on the energy consumption from auxiliary systems such as the HVAC equipment which could lead to a decrease in the consumptions up to 41.03% when used in EV [5]. According to the EU Directive 2003/30/CE regarding the energy consumptions at the European level, more than 30% of the final energy consumptions in Europe are due to transportation [6]. Furthermore, the usage of the electrical energy in vehicle transportation requires a deep interest in the HVAC systems in order to maintain the maximum comfort levels with
the minimum energy effort. Hence, phenomena such as condensation on the glass side of the interior vehicle and condensation elimination, must be treated with more care. Being a phase change phenomenon, the energy consumption can be highly raised, on one hand and it can lead to safety issues if not treated correctly during driving periods on the other. Nonetheless, due to the fact that the electric vehicles are benefiting from less residual heat in comparison with the energy needed to maintain the interior comfort conditions and to prevent the interior condensation process, the HVAC systems lead to an increase in the energy consumption, while having a significant impact in lowering the driving range. As regards to the ICEV, for the summer period, the HVAC system may lead to a raise in the energy consumption up to 20% \[7\]. Other study showed that the Air Conditioning (AC) unit might be responsible for lowering the power range by 30-40% depending on the type of car and the type of AC unit \[8\]. Further on, by means of a climatic chamber, it was determined the maximum energy consumption for the HVAC unit at an exterior temperature of -30 \(^\circ\)C, while the minimum results in energy consumption were determined for an outdoor temperature of 23 \(^\circ\)C \[9\]. Literature study showed that the electric vehicles present in general a driving range of 200 km. However, this driving range in significantly reduced up to 40% by the HVAC system usage \[1\].

As concerns the condensation process, there are three methods through which the de-icing/defogging are combated and prevented. One would be by using the HVAC system to heat up the air and then introduce it at the interior through grids placed on the dashboard or by using electric resistances (ER) placed between layers of glazing surface. Another method would be represented by the usage of an AC unit which would cool the air in order to reduce the humidity level \[10\]. The usage of electric wires represents a fast and simple tool to resolve the issue of visibility and condensation, but the impact on energy consumption seems to push further in finding new solutions. Therefore, a hybrid solution between the air handling units and electrical resistance might become a better answer \[11\].

The importance of the condensation process while driving is mostly highlighted through visibility issues. For instance a study showed that when subjected to low visibility, the inexperienced drivers were more predisposed to collision due to their long response time \[12\]. Furthermore, a study conducted for the tram drivers revealed serious visibility problems and draw attention to the serious need for improvement of the demisting system \[13\].

Besides the impact of the relative humidity the fogging and misting issues inside a vehicle are influenced also by the amount of airflow and the flow homogeneity, the angle of the windshield along with the angle and position of the demisting ducts \[14\]. According to EU 78-317-EEC the performance of a demisting system for vehicles must be able to perform a clear windshield for an area A in front of the driver which should be demisted in proportion of 90% after 10 minutes from the moment when the demisting process had started and a larger area named area B which should be demisted in proportion of 80% after 10 minutes \[15\]. Similar legal documents presenting almost the same procedure for demisting and de-icing of the glazing surfaces are present also on other continents such as Australia \[16\], United States of America \[17\].

The appearance of condensation in a vehicle’s cabin is dependent on the indoor air temperature, exterior temperature and weather conditions, solar radiation, relative humidity, occupants etc. The growth of relative humidity inside the indoor environment is dependent also on the numbers of air changes per hour. However, these air changes affect at the same time, the thermal comfort and the energy consumption \[18\]. Therefore, a balance between the thermal comfort, demisting system usage and energy consumption should be maintained. During the demisting process the condensation film needs additional energy to evaporate the water and further on, to eliminate the humid air to the exterior environment.

2. The condensation phenomenon

When the condensation takes place in the bulk of the fluid the phenomenon is called homogenous condensation. On the other hand, heterogeneous condensation or surface condensation represents the phase change phenomenon in which the water vapours within the air volume are transformed in water droplets when they meet a solid surface level \[19\]. This phenomenon takes place when the temperature
of the surface drops below the dew point temperature. As the temperature is dependent on pressure level, the condensation phenomenon can occur when the pressure drops below the saturation pressure. Moreover, the heterogeneous condensation can be classified as follows: filmwise condensation when the condensation is taking the form of a continuous layer at the solid surface level or dropwise condensation, when the condensation is taking a rather non-continuous form of scattered droplets on the solid surface [19].

![Heterogeneous condensation](https://www.sciencedirect.com/topics/engineering/condensate-film)

**Figure 1.** Heterogeneous condensation, filmwise (a) and dropwise (b) condensation (source: https://www.sciencedirect.com/topics/engineering/condensate-film)

The type of heterogeneous condensation that could appear on a solid surface depends on several parameters, such as, adhesive forces, water contact angle [20], wettability [21], condensation sites [22] etc. The adhesive forces determine the attraction forces between the water molecules and other surfaces leading to a retain the water molecules near the solid surface. On the other hand, the water contact angle represents the angle formed between the water droplet and the solid surface. Therefore, an angle greater than 90° signifies a hydrophobic surface, while an angle smaller than 90° presents a hydrophilic surface.

![Water Contact Angle and surface wettability](http://www.sciencebrainwaves.com/ultra-ever-dry/)

**Figure 2.** Water Contact Angle and surface wettability (source: http://www.sciencebrainwaves.com/ultra-ever-dry/)

Further on, the presence of condensation sites determines the place where the condensation phenomenon appears. These condensation sites might be natural cavities found on the solid surface, but they can be also represented by artificial nucleation sites such as scratches [23]. Moreover, the presence of other particles on the surface might influence the condensation phenomenon either by accelerating its appearance or by inhibiting it [23].
The condensation process can be analysed and quantified through numerical, experimental or even analytic processes. The most common and accurate results are usually based on experimental or numerical studies. Therefore, within the next paragraphs the focus will be on these two approaches.

3. Experimental approach in condensation phenomenon

Nguyen et al. [24] studied the appearance, the evolution and the quantity of the condensation mass on the real scale glazing surface placed inside a climatic chamber. The main equipment involved were a highly resolution photo camera, multiple sensors and a recording camera. The place, the quantity and the evolution of the condensation process on the glazing surface was determined using image processing method by means of Python software [24]. On the other hand, Lorentz [25] proposed an experimental approach at a smaller scale using a 50x50x2 mm polycarbonate surface placed inside a climatic chamber. In order to determine the volume of the droplets, the paper developed a new technique which involved determining the water contact angle based on the reflexion of the light. The procedure involved a source light placed perpendicular on the glazing surface and a high-resolution camera. Based on a MathLab algorithm, the volume and the contact angle of every droplet was determined [25].

Other experimental studies tackled the condensation and evaporation process inside vehicles with the purpose of obtaining an analytical model that could determine the interior conditions and prevent its appearance. For instance, by placing a vehicle inside a climatic chamber with several humidity and temperature sensors the condensation occurrence was studied. The experimental results were then transformed into a mathematical equation which can determine the point when the condensation might appear. The equation depends on the interior relative humidity $r_{\text{in}}$, correction factor depending on the vehicle’s speed $F_w$, interior temperature $T_{\text{in}}$ and $\alpha$ and $\beta$ determined experimentally by means of ASHRAE brochure on Psychrometry [26].

$$r_{\text{in}} = 100 - \frac{\alpha(1 - F_w)(T_{\text{in}} - T_{dp})}{\beta + (1 - F_w)(T_{\text{in}} - T_{dp})}$$ (1)

San-Juan M. et al. [27] focused on determining the impact of the vehicle’s type on the defogging and de-icing systems. The study involved three Renault cars: an IECV, an electric vehicle using electrical resistance for heating and an electric vehicle using a heat pump. The results were determined by means of a thermographic camera placed 4 m in front of the vehicle, perpendicular on the windshield. The purpose of the experimental campaign was to determine the importance of the type of vehicle and type of HVAC system on the defogging and de-icing phenomenon [27].

![Figure 3. Temperatures’ evolution on the windshield](image)

The results of this study showed that the system requires at least 4 minutes in order to achieve a 10 °C temperature at the windshield level for a certain surface in front of the driver. Furthermore, the EV using a heat pump involved the shortest time in order to achieve the exact temperature, in comparison
with the ICEV which required 10 minutes. Moreover, the EV-HP reached first the 20°C temperature at the windshield level after 3.4 minutes, while the ICEV vehicle needed a lot more, more exactly 8.8 minutes [27]. To conclude the experiment, the electric vehicles are more efficient when used for defogging and de-icing reaching easily the expected temperatures regardless of the type of HVAC equipment.

The experimental campaign held by Kang et. al. [28] for a diesel vehicle utilizing a thermographic camera (IR) placed 3 m in front of the main glazing surface of the vehicle, highlighted the non-uniformity of the windshield temperature [28]. The results proved a higher temperature for the lower windshield part with a drop in temperature values for the higher part. Moreover, during the experiments the temperature levels went up during the first 20 minutes of functioning.

![Figure 4. Measured temperature contour [28]](image)

In another experimental study the temperature and the air velocity were investigated for the windshield level. Aroussi et. al. [18] used several hot bulb probes placed 5 mm in front of the windshield and a thermographic camera placed 3 m in front of the vehicle [18]. The results showed that the velocity contours are higher for the lower windshield part 1 m/s, whilst they significantly drop at the higher part at about 0.2 m/s.

![Figure 5. Velocity contours windshield [18]](image)

Table 1 centralises some important work that has been done on the subject of condensation and demisting/de-icing of windshields in vehicles’ cabin using an experimental approach. The table presents the authors, the year of article’s publication, the objectives set for the paper and a set of conclusions together with their discoveries during the research period.
Table 1. Presentation of experimental studies

| Author               | Year | Objectives                                                                 | Conclusions                                                                 | Discoveries                                                                                                                                                                                                 |
|----------------------|------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Gerstmann and Griffith [29] | 1966 | Heat transfer determinations for condensation phenomenon at a flat plate level by differing the slope angle - theoretical model. | Although the condensation phenomenon is transient, the condensation rate can be determined through a steady state hypothesis. | The condensation results for both, horizontal and vertical surfaces, can lead to errors up to 25% in comparison with the experimental values. These errors might be caused by the steady state simplification hypothesis. |
| Griffith and Lee [30] | 1967 | Evaluation of the physical, thermal and mechanical parameters, which influence the characteristics of the type of condensation. | For water vapor condensation at the atmospheric pressure on a horizontal surface, heat transfer coefficient is independent on the surface's roughness. | An important property for droplet condensation is represented by the thermal conductivity of the analysed surface. |
| Davis et. al. [26]    | 2001 | Strategy for fogging and demisting prediction and/or appearance reduction using an ATC (Automated Temperature Controller). | Interior condensation appearance is influenced by the HVAC system and vehicles’ interior characteristics. | The novel strategy proposed within the paper might present some limitations due to differences of the HVAC components. |
| Kang et. al. [28]     | 2010 | Numerical validation through experimental determination for the defogging phenomena at a vehicle's windshield. | The numerical approach presented similar results with the experimental campaign, the deviation between the two being approximatively 5%. | The air introduced through the interior grids doesn’t cover entirely the windshield causing condensation appearance. |
| Steiner and Rieberer [10] | 2013 | Examination of the windshield de-icing process for an EV using a HP.          | The exterior heat exchanger needs to be de-iced in order to be used properly. This can be done through a 2 minutes inversion of the operating cycle. | The article draw attention over the HP limitations when used as HVAC systems in EV. |
| Lorenz [25]           | 2015 | Proposal of new ventilation concepts for energy reduction in a vehicle's cabin, especially for defogging/de-icing phenomena. | A configuration with 50% air recirculation, window and chairs heating and a reduction in air temperature up to 12 ° C, maintains the interior comfort conditions together with an important energy consumption reduction. | Proposal of a novel condensation analysis and quantification through an experimental approach. |
| Chang et. al. [31]    | 2016 | Quantification of the air infiltrations inside a vehicle.                    | When the car presents only one occupant, the fresh air necessity can be accomplished only by setting the fan at the minimum level in stationary conditions. | Proposal for a novel theoretical equation validated through experimental campaign. |
| Author          | Year | Objectives                                                                 | Conclusions                                                                 | Discoveries                                                                 |
|----------------|------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| San-Juan et. al. [27] | 2016 | Evaluation of the defogging system for various types of vehicles.            | There is a strong need to increase the performance levels of the HVAC systems in vehicles. | The defogging systems for ICEV are less effective than the ones in EV. The EV using an HP are less energy consuming than the EV using ER. |
| Nguyen [19]    | 2018 | Quantification analysis of the condensation process on a glazed surface.    | Image process technique can be highly effective for condensation quantification. | There is a lack in condensation analysis in the specialized literature, therefore the results in this study are extremely valuable. |
| Danca [32]     | 2018 | Development of a thermal manikin capable of a great thermal evaluation of the cabin interior comfort. | The thermal manikin represents an indispensable instrument in thermal comfort evaluation for both, laboratory tests and real case studies. | There were notable differences between the results obtained by means of the Thermal Manikin and the ones from surveys completed by human subjects. |
| Pan et. al. [33] | 2019 | Evaluation of the ventilation recirculation module and its impact on the energy consumption of vehicles. | Choosing a recirculation ventilation module can lead to a decrease between 14% - 46% in energy consumption in vehicles. | Choosing a HP system can lead to an economy of 33% - 57% in energy consumption in vehicles. |
| Arvidsson et. al. [34] | 2019 | Energy consumption reduction due to defogging/de-icing procedures in electrical buses. | Usage of radiation heating devices can drastically reduce the energy consumption in electrical buses. | Although, the novel system proposed presents multiple disadvantages, it is still more efficient in comparison with the traditional system. |

4. Numerical approach for determining the performance of defogging and demisting system inside a vehicle’s cabin

Determining the place, the time and the amount of condensation which appears on a solid surface can be also tackled through a numerical approach, more precisely a CFD (Computational Fluid Dynamics) technique. This method presents multiple advantages because it is the only technique which can incorporate physical phenomena such as heat and mass transfer, phase change, chemical reactions and combustion, mechanical movements, whilst it is less time – consuming and requires a lower financial cost in comparison with an experimental approach. Therefore, applying a numerical approach for both, simple and complex situations has been developing a lot in the past few years.

As regards to modelling the phase change phenomenon, there are two methods through which this phenomenon could be tackled such as, monophasic models or biphasic models. The biphasic models require simultaneous studies for the two types of fluid flow and water vapours, both containing different viscosities [35]. Furthermore, this approach also takes into consideration droplet movements or water film separation. However, this method is usually used for industrial applications as there is a strong need to raise the heat transfer which can be done through raising the amount of condensation. Furthermore, this approach requires more computerised resources as the number of formulas to model the phenomenon is doubled for the air and water vapours and also for the liquid state [35]. Bearing this...
in mind, for the building applications where the amount of condensation is not that significant, the simpler solution of monophasic model has been chosen so far.

A monophasic numerical model for determining the condensation process was developed by Teodosiu [36]. This approach can be explained through the transport equation containing all the terms for convective diffusion and both, molecular and turbulent diffusion. Therefore, the first term at the left of equation (2) represents the convection due to different densities $\rho$, the velocity towards $i$ direction $u_i$, water vapor mass fraction $m_i'$. The second term represents the diffusion factor and consists of diffusion flux of water vapours $J_{i',i}$, whilst the $S_i$ represents the source term [36]:

$$\frac{\partial}{\partial x_i}(u_i m_i') + \frac{\partial}{\partial x_i} J_{i',i} = S_i$$

The diffusion term was further explained in equation (3) where the first term on the right side represents the molecular diffusion term, whilst the second term on the right is represents the turbulence diffusion.

In order to obtain the heat transfer coefficient for convection $h_c$, the following hypothesis was implemented, the near solid region is characterised by the heat diffusion phenomenon, while the convection heat transfer has a lower influence. Hence, the thermal flux density can be expressed as an equality of both phenomena:

$$\varphi = \lambda_{air} \frac{\partial T}{\partial n} = h_c (T_F - T_{CO}) \Rightarrow h_c = \frac{\lambda_{air} \frac{\partial T}{\partial n}}{(T_F - T_{CO})}$$

Where $\lambda_{air}$ represents the heat transfer coefficient through conduction, $T_F$ the temperature of the solid surface in the sub-viscous layer, $T_{CO}$ represents the temperature in the centre of the near wall cell [36].

The condensation mass on the solid surface was determined using the following expression depending on the heat transfer convection coefficient, $S_C$ represents the surface, interior air vapor pression $P_{vap.air}$ and vapour pression on the solid surface $P_{vap.surface}$ [36]:

$$m_{liq.surface} = 7.4 \cdot 10^{-9} h_c S_C (P_{vap} - P_{sat})$$

Based on this model, Ilie [35] continued the studies and proposed some improvements to the model, such as, introduction of radiative heat transfer, implementation of latent and sensible energy. This improvement was accomplished by moving the latent and sensible energy resulted from the water vapours condensation from the fluid cell centre into the source term of the solid cell [35].

The comparison of the two models showed an improvement of the glazing solid surface of 0.3 ◦C [35].
Other studies showed the influence of new geometries for the air introduction in vehicles and their influence on the de-icing and defogging processes [37].

The numerical analysis was done by using the $k-\varepsilon$ Realizable turbulence model and contained more than 10 000 000 hybrid cells grid [37].

The results showed an improvement of velocity scales and furthermore in temperature for the first configuration which were also supported by the experimental campaign [37].

Shojaefard et. al. [38] studied the influence of low exterior temperature on a vehicle’s windshield through a numerical approach by means of Ansys Fluent. The results showed that for an exterior temperature of -8 °C, there is a need of at least 15 minutes reach 0 °C for the driver seat zone and 25 minutes to reach the same temperature of 0 °C for the entire windshield. Nonetheless the EU directive for safety driving conditions is met [15]. Furthermore, the study highlighted that there is a strong need
to improve the HVAC systems and its influence on the energy consumptions, comfort conditions and safety during driving periods.

Table 2 centralises some important work that has been done about condensation and demisting/de-icing of windshields in vehicles’ cabin using numerical simulations, generally based on parameters obtained experimentally. The table presents the authors, the year of article’s publication, the objectives set for the paper with the software used, a set of conclusions and highlights of the discoveries.

| Author            | Year | Objective                                                                 | Software   | Conclusions                                                                                                                                  | Discoveries                                                                                     |
|-------------------|------|---------------------------------------------------------------------------|------------|---------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Doroudian [39]    | 2002 | CFD technique utilization for defogging prediction and efficiency evaluation for vehicle applications. | Fluent      | The CFD approach can be used for testing and proposal of new equipment which can present great improvement in energy consumptions and efficiency. | Presentation of the steps required in a CFD approach for defogging/de-icing concepts in vehicles. |
| Aroussi et. al. [40] | 2003 | Development of a numerical model for demisting evaluation in vehicles.     | Ansys Fluent | The CFD technique can be successfully applied for fluid flow and heat transfer analysis in vehicles.                                       | Emphasis on the significant disadvantages of the actual systems.                                 |
| Croce et. Al. [41] | 2005 | Prediction of the condensation/evaporation phenomena on solid surfaces.   | CFX 5.5    | Validation of the defogging numerical model by means of experimental campaign.                                                               | By considering a continuous filmwise condensation instead of a discontinuous coating, can lead to an overestimation of the defogging time up to 70%. |
| Sandhu [42]       | 2011 | Discussion on the parameters which are influencing the evaporation/conden-nsation phenomenon and methods for defogging the glazing surfaces in vehicle's cabin. | STARCCM+    | CFD models can be used successfully for predicting the performance of the defogging equipment.                                                | More complex CFD models should be used for defogging process on vehicle glazing surfaces.        |
| Kang et. al. [28] | 2011 | Numerical validation through experimental results of the defogging phenomenon on a vehicle's windshield. | Scryu Tetra | There was a deviation of 5% between the results obtained through numerical approach in comparison with the experimental campaign.            | The actual systems present non-uniformity in the air jet which leads to "dead" zones favorizing condensation phenomenon. |
| Author          | Year | Objective                                                                 | Software | Conclusions                                                                 | Discoveries                                                                                                                                 |
|-----------------|------|-----------------------------------------------------------------------------|----------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------|
| Teodosiu et al. | 2013 | Proposal of a numerical model for water vapor condensation inside rooms.    | Fluent   | The numerical model proposed within the paper leads to accurate results of the convection phenomenon inside enclosed spaces. | For accurate results, it is recommended to make use of a model which deals with the condensation process in a quasi-stationary state.       |
| Verma [43]      | 2014 | Proposal for a new defogging method for the lateral glazing surfaces in vehicles' cabin. | Fluent   | The system proposed in this paper presents multiple benefits for increased visibility during driving sessions. | The advantages and limitations of the newly proposed system.                                                                                   |
| Jahani et. al.  | 2014 | Proposal of two new air ventilation grids and results through CFD methods.  | CAE tools| The CFD approach is a great tool to use for the development of interior geometries inside a vehicle’s cabin. | Proposal of the optimal geometry of the air pipes in order to obtain a minimum pressure loss at a maximum air rate.                       |
| Teodosiu et al. | 2014 | Evaluation of the turbulence performance models for air flow predictions inside enclosed spaces. | Fluent   | The k-ω turbulence model might represent an interesting alternative for the LES models. Furthermore, the k-ω models require less computational resources. | For more accurate results within enclosed spaces, it is recommended to use the SST k-ω model with four equations.                     |
| Shojaeefard et. al. [38] | 2015 | Evaluation of the HVAC system in vehicles using a CFD approach.            | Fluent   | 15 minutes are needed in order to de-ice zone A of the windshield at an exterior temperature of 8 °C. | The defogging/de-icing requirements from the ECE-78-715 standard can be relatively easy fulfilled.                                  |
| Sadananda [45]  | 2016 | Improvements of the CFD prediction models for de-icing vehicle's windshields. | Fluent   | Air introduction by usage of defogging grids with 2 m/s leads to a homogenous air distribution, while a 3 m/s leads to air jet separations at the windshield. | For steady state de-icing application inside vehicle, the k-ε Realizable model presents better results in comparison with the k-ω SST model. |
| Mortensen et al. [46] | 2016 | CFD model description for heat and mass transfer through building’s envelope. | Fluent   | Setting the walls as a fluid environment can provide the basic step for water vapours permeability at a building level. | Interior furniture can massively influence the interior microclimate. Thus, the furniture shouldn't be excluded from numerical humidity simulations. |
| Ilie [35]       | 2017 | Quantification of dropwise condensation on a glazing surface in time.     | Fluent   | In comparison with the k-ω SST model, the k-ε model presents better results for enclosed spaces fluid flows. | The condensation model proposed within this paper takes into consideration the heat transfer through radiation.                         |
5. Conclusions

The energy consumption due to vehicle transportation represents more than 30% [6] of the final energy consumption at the European level with a massive growing potential. The evolution towards electric transportation leads to a growing concern regarding the usage of the HVAC systems during driving periods as they could significantly reduce the power train and the driving range. Thus, there is a strong need to improve the HVAC vehicle' system, especially for the defogging and de-icing procedures. As they are phase change processes, the energy consumption is substantial. The paper presented some of the most important experimental procedures which could be used in order to determine the amount and the place of the condensation formation together with the equipment required for the task. Furthermore, the paper highlighted the studies carried out in the mentioned field and the benefits of HVAC system improvement. Further on, the insights of using a numerical approach in determining the condensation/evaporation process based on different specialty literature studies were showcased. The methods of tackling the condensation – evaporation phenomenon, the introduced parameters, the type of software and the CFD models chosen, all have been presented in the paragraphs above.

References

[1] Zhang T et al., Status and development of electric vehicle integrated thermal management from BTM to HVAC, Applied Thermal Engineering, 88, pp. 398-409, 2015.

[2] Patil M S, Cho C-P, and Lee M-Y, Numerical study on thermal performances of 2.0 kW burner for the cabin heater of an electric passenger vehicle, Applied Thermal Engineering, 138, pp. 819-831, 2018.

[3] Castro Verdezoto P L, Vidoza J A, and Gallo W L R, Analysis and projection of energy consumption in Ecuador: Energy efficiency policies in the transportation sector, Energy Policy, 134, 2019.

[4] ([Accessed 29.10.2019]). https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases/transport-emissions-of-greenhouse-gases-11.

[5] Zhang Z, Liu C, Chen X, Zhang C, and Chen J, Annual energy consumption of electric vehicle air conditioning in China, Applied Thermal Engineering, 125, pp. 567-574, 2017.

[6] Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the Promotion of the Use of Biofuels or other Renewable Fuels for Transport, 2003.

[7] Payá J, Corberán, J.M., Torregrosa-Jaime, Vasile-Müller, Innovative Air-Conditioning Systems for Conventional and Electric Vehicles, 2010.

[8] Zhang Z, Wang J, Feng X, Chang L, Chen Y, and Wang X, The solutions to electric vehicle air conditioning systems: A review, Renewable and Sustainable Energy Reviews, 91, pp. 443-463, 2018.

[9] Galassi M C, Stutenberg, K., Garcia Otura, M., Trentadue, G., Scholz, H. W., Carriero, M., Electric and hybrid vehicle testing (Luxembourg: Publications Office of the European Union). 2018.

[10] Steiner A and Rieberer R, Parametric analysis of the defrosting process of a reversible heat pump system for electric vehicles, Applied Thermal Engineering, 61, no. 2, pp. 393-400, 2013.

[11] Unverdi S O, Eren H, Erdem V, Sonmez N, Emre A, and Bayraktar V, Technical note: Optimisation of the defroster ducts and windshield electric resistances of a city bus with CFD analysis, International Journal of Vehicle Design, 52, no. 1/2/3/4, pp. 199 - 121, 2010.
[12] Mueller A S and Trick L M, Driving in fog: The effects of driving experience and visibility on speed compensation and hazard avoidance, Accident Analysis & Prevention, 48, pp. 472-479, 2012.

[13] Guesset A, de Labonnefon V, and Blancheton M, Ergonomics and Visibility in Tramway Driving Cab, Transportation Research Procedia, 14, pp. 585-594, 2016.

[14] Sen S, Selokar M, Nisad D, and Kishore K, Design and Development of Demisting Device of a Commercial Vehicle and its Numerical As Well As Experimental Validation, presented at the SAE Technical Paper Series, 2016.

[15] Council Directive 78 /317/EEC of 21 December 1977 on the approximation of the laws of the Member States relating to the defrosting and demisting systems of glazed surfaces of motor vehicles, 1977.

[16] Vehicle Standard (Australian Design Rule 8/01 – Safety Glazing Material), 2005.

[17] U.S. Department Of Transportation National Highway Traffic Safety Administration, Laboratory Test Procedure For Fmvss 103, Windshield Defrosting and Defogging Systems, 1996.

[18] Nguyen C-K, Full-scale experimental characterization of a non-isothermal realistic air jet for building ventilation: local interaction effects, moisture transport and condensation, Université de Lyon, 2018.

[19] Durán I R and Laroche G, Current trends, challenges, and perspectives of anti-fogging technology: Surface and material design, fabrication strategies, and beyond, Progress in Materials Science, 99, pp. 106-186, 2019.

[20] Zanganeh P, Goharrizi A S, Ayatollahi S, Feilizadeh M, and Dashti H, Efficiency improvement of solar stills through wettability alteration of the condensation surface: An experimental study, Applied Energy, 268, 2020.

[21] Mu C, Pang J, Lu Q, and Liu T, Effects of surface topography of material on nucleation site density of dropwise condensation, Chemical Engineering Science, 63, no. 4, pp. 874-880, 2008.

[22] J. L. McCormic K J W W, Nucleation sites for dropwise condensation, Chemical Engineering Science, 20, no. Pergamon Press Ltd., Oxford, pp. 1021-103, 1965.

[23] Nguyen C-K, Teodosiu C, Kuznik F, David D, Teodosiu R, and Rusaouén G, A full-scale experimental study concerning the moisture condensation on building glazing surface, Building and Environment, 156, pp. 215-224, 2019.

[24] Lorenz M, Reduction of heating loads and interior window fogging in vehicles, Technische Universität München Institut für Energietechnik, 2015.

[25] L. I. Davis J G A D, J. D. Hoeschele, Conditions for incipient windshield fogging and anti-fog strategy for automatic climate control, SAE 2001 World Congress, Detroit, Michigan, 2001.

[26] San-Juan M, Martín Ó, Mirones B J, and De Tiedra P, Assessment of efficiency of windscreen demisting systems in electrical vehicles by using IR thermography, Applied Thermal Engineering, 104, pp. 479-485, 2016.

[27] Kang S J, Kader M F, Jun Y D, and Lee K B, Automobile defrosting system analysis through a full-scale model, International Journal of Automotive Technology, 12, no. 1, pp. 39-44, 2011.
[29] Joseph Gerstmann P G, Laminar Film Condensation on the Underside of Horizontal and Inclined Surfaces, *Hear Moss Transfer*, 10, pp. 567-580, 1966.

[30] Peter Griffith M S L, The Effect of Surface Thermal Properties and Finish on Dropwise Condensation, *Hear Moss Transfer*, 10, pp. 697-707, 1967.

[31] Chang T-B, Sheu J-J, and Huang J-W, Vehicle air leakage ventilation and its effect on cabin indoor air quality, *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, 231, no. 6, pp. 1226-1234, 2016.

[32] Danca P A, Stratégies de ventilation pour l’amélioration de la qualité de l’environnement intérieur dans les véhicules, *Université de Rennes 1/Universitatea Tehnică de Construcții București*, 2018.

[33] Pan L, Liu C, Zhang Z, Wang T, Shi J, and Chen J, Energy-saving effect of utilizing recirculated air in electric vehicle air conditioning system, *International Journal of Refrigeration*, 102, pp. 122-129, 2019.

[34] Erik Arvidsson W B, Edvin Johansson, Lucas Jutvik, Anthony Nusca, Jonathan Petterson, Design of an Energy Efficient Windshield Defrosting System for Electric Transit Buses, *Bachelor’s Thesis*, *Chalmers University of Technology, Polytechnique Montreal*, 2019.

[35] Ilie V, Studiul Fenomenelor de Transfer de Căldură și Masă în Încăperi Climatizate, 2017.

[36] Teodosiu R, Integrated moisture (including condensation) – Energy–airflow model within enclosures. Experimental validation, *Building and Environment*, 61, pp. 197-209, 2013.

[37] Kambiz Jahani S B, Utilizing CFD Approach for Preeminent Assessment of Defroster Air Flow Distribution and Predicting Windscreen Deficing Behavior, presented at the SAE Technical Paper Series, 2014.

[38] M. H. Shojaee-Tafreshi G R M, N. Aghamirzaei, S. Ghezelbiglo, B. Zeinolabedini, Numerical evaluation of the defrosting/defogging performance of HVAC system in the main product of the national vehicle platform, *International Journal of Automotive Engineering*, 5, pp. 2006-2016, 2015.

[39] Doroudian M, Numerical Simulation of Automobile Windshield Defogging.

[40] Aroussi A, Hassan A, and Morsi Y, Numerical simulation of the airflow over and heat transfer through a vehicle windshield defrosting and demisting system, *Heat and Mass Transfer*, 39, no. 5, pp. 401-405, 2003.

[41] Croce G, D’Agaro P, and Della Mora F, Numerical simulation of glass fogging and defogging, *International Journal of Computational Fluid Dynamics*, 19, no. 6, pp. 437-445, 2005.

[42] Sandhu K S, Predicting the windscreen demisting performance using CAE, in *Vehicle Thermal Management Systems Conference and Exhibition (VTMS10)*, 2011, pp. 401-410.

[43] Mukesh V, Experimental study for the improvement of vision through side window of a car during rain, *Dissertation Thesis, Thapar University*, 2014.

[44] Catalin Teodosiu V I, Raluca Teodosiu, Appropriate CFD Turbulence Model for Improving Indoor Air Quality of Ventilated Spaces, *Mathematical Modelling in Civil Engineering*, 10, 2014.

[45] Sadananda T, "Improving the Accuracy of CFD Method for Windscreen Deficing," Chalmers University of Technology Goteborg, Sweden - Disertation Thesis, 2016.

[46] Mortensen L H, Woloszyn M, Rode C, and Peuhkuri R, Investigation of Microclimate by CFD Modeling of Moisture Interactions between Air and Constructions, *Journal of Building Physics*, 30, no. 4, pp. 279-315, 2016.