Analyzing Alternatives in the Scope of Product Design and Development for Effective Control towards Defogging in an Automotive Cabin

Swapnil S. Kulkarni[1] R. K. Agrawal[2] Rahul kharat[3]
[1,2,3]Department of Mechanical Engineering
[1,2]University of Mumbai India [3]College of Engineering Pune, MBA, IIM Lucknow, IPMX India

Abstract— Passenger safety is considered as the central issue in vehicle design since many years. One of the important factors that strongly affect driving safety is visibility through the windshield. Tools available for this purpose are sensor based and may lead to misfiring. Mathematical models available largely do not account the effects of latent heat and humidity. The performance of the A/c in the light of `Defogging' involves thermal parameters to be controlled while the Product Design and Development of the same involves tools to be deployed in realizing a commercial product. Both the aspects shall be evaluated with emphasis on the `Product Development' of the solution. The model shall help in predicting fogging and understanding the actual thermal parameters leading to it and hence can be useful in optimizing these parameters so as to reduce fogging. It should serve as a useful tool in optimizing the performance of an air conditioner while making the product viable for development and manufacturing further.

Key words: Car Air-Conditioner, In-Cabin Condensate, Defogging, Product Development, FMEA

I. Introduction

The term "Fogging" refers to the film that collects on the inside of vehicle window glass. Of particular interest is the windshield, because this film can both limit light transmission as well as refract the light that is transmitted, impairing visibility and creating safety concerns. A fogging test system is designed to determine the fogging value as defined in the various standards as well as compare types of materials used in vehicle cabins.

Passenger safety has been considered as the central issue in vehicle design since many years. One of the important factors that strongly affect driving safety is visibility through the windshield. The presence of fog on the windshield glass reduces or blocks the field of vision for the driver. A distracted driver endangers both himself and other drivers sharing the road. Climate control systems have been developed and are widely used for minimizing such problems. The climate control system also increases the sensation of thermal comfort in the car compartment and thereby affects greatly the driver's concentration and enhances safety of the passengers.

A. Causes of Fogging

Most of us have seen some kind of fogged window. A fogged window is not exactly the same as fog in the air. Fog can happen for a multitude of reasons, but before we know why fog happens, we need to know what it is. Fog is a mass of thick moisture or water droplets. Sometimes fog is airborne, especially in near bodies of water. Other times it appears on surfaces. If you've wondered why fog often appears on windows, it's mainly due to the temperature difference between the two sides of the thin glass surface. Cold weather brings with it lots of frost and fog. The reason for this is the temperature difference between the inside and outside of your car. The heat from the inside of the car warms up the frost around the window and under the hood of the car. The moisture from the frost then sticks to the window as fog, trapped in a limbo of temperature changes. Likewise, the inside of the car window fogs when the moisture of the warm air comes into contact with the cold glass of the window. There are times when fog is already present outside. In areas with large bodies of water, wind currents, as well as temperature changes throughout the day can create fog. Wind travelling and cooling as it moves up mountains results in perpetual fog for seasons, or even year-round. These conditions can't be prevented or avoided by drivers and are persistent. Excessive moisture on the outside or inside of a car can lead to window fogging. While some causes like rain and snow can fall into the outside conditions category, their effect is two-fold, landing them a spot here. Moisture left by outside conditions can accumulate in your car, staying there for long periods until redistributed back into the air. A common place this happens is the air conditioning, which can lead to sudden fogging of windows. Sweat, heavy breathing, pets, damp shoes and clothing as well as food and beverages in a closed space can also lead to moisture collecting over time.

II. Literature Review

G. Croce, P.D. Agaro&etal. [1] Studied a suite of routines for the prediction of environment moist condensation and evaporation on solid surfaces. Scott Pratt [2] studied about High surface and interior temperatures cause the polymers, textiles and natural materials used in automotive interiors to outgas volatile and semi-volatile organic compounds (VOC and SVOC) at an accelerated rate. ResatSelbas [3] studied that A heat exchanger is a device that is used to transfer heat between two or more fluids that are at different temperatures. Serge Ulrich [4] studied about Computer Simulations of Homogeneous Deposition of Liquid Droplets. PAYÁ, J., CORBERÁN, J.M. [5] proposed an innovative air-conditioning system for conventional and electric vehicles. ThiagoLuísZolet [6] proposed a CFD and experimental correlation of the defrost flow and vehicle's windshield defogging. Scott Pratt [7] studied about High surface and interior temperatures cause the polymers, textiles and natural materials used in automotive interiors to outgas volatile and semi-volatile organic compounds (VOC and SVOC) at an accelerated rate. PAYÁ, J., CORBERÁN, J.M. [8] proposed an innovative air-conditioning system for conventional and electric vehicles. The heating and cooling systems are a major challenge in the development of electric vehicles (EVs).

III. Problem Definition

The fog observed within the cabin space in an automotive vehicle poses a safety hazard due to reduced visibility for the driver and other occupants. The moisture eventually condenses on the windshield. The common method of overcoming this problem is to use heater. The dew point of the saturated air, if raised, reduces the amount of fog evident as a condensate over the windshield. Although, this leads to undesired rise in the cabin space temperature. Therefore, localized means of heating the windshield could be considered for dealing with the problem. This shall be the subject matter for this thesis work.

The effort to introduce localized heating could be expedited either by creating heating nodes over designated areas of the windshield so as not to obstruct the vision. Alternatively, a transparent or translucent layer over the windshield that would respond heating induced by a heating element transversing the length or width of the windshield. This may be thought of as fitting a heating coil in the wiper of the windshield! The coating might include powdered metal for stimulating the rate of heating. Other alternatives might be conceptualized and assessed for realizing effective defogging of the cabin space, especially the windshield.

The Product Development aspect needs to be dealt with through tools like DFM for realizing a commercial product in the long run. The scope of this work shall be limited to proposing a Design for those elements in the system that could be critical to manufacture or for developing the product as a whole.

IV. OBJECTIVES

- Study the existing vehicle system and literature survey related to defogging techniques used in automotive vehicle.
- Identify the causes of fogging
- Identify the different materials used for this system
- To study the standards available for Fog test in automotive application.
- Mathematical Model for calculating the moisture of glass
- Design and analyse the model for new heating elements to introduce in windshield

V. METHODOLOGY

A. Mathematical Modeling

1) Glass Model

Initially fogging on a piece of glass plate was studied. Model equations were developed to study simultaneous heat and mass transfer from a glass plate while fogging/defogging. This model was then used for the modeling of car cabin.

2) Model Equations for Glass

a) Heat Balance Equation

Rate of change of energy at the surface = Sensible heat gain + Latent heat gain

$$\frac{d}{dt}\left(\rho_g V_g C_p T_g\right) = h_g A_g (T_{amb} - T_g) + k_w \lambda A_g (\omega_{amb} - \omega_g) \quad (1)$$

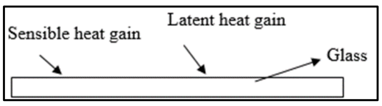

Fig. 1: Heat balance

b) Moisture Balance Equation

Rate of change of moisture at the surface = Condensation or Evaporation of moisture at the surface.

$$\frac{d}{dt}(m_w) = k_w A_g (\omega_{amb} - \omega_g) \quad (2)$$

3) Modified Glass Model

This model is based on the paper by Giulio Croce et.al. In this model A_g in the above equations is not constant for latent heat transfer but it varies accordingly with the amount of condensation and vaporization. It is calculated as:

$$A_g = \Pi d^2 / 2 \quad (3)$$

This is characterized by calculating droplet diameter from the equation:

$$d = \frac{12\sqrt{3}(\sin \nu)^3 H}{\pi(1 - \cos \nu)^2 (2 + \cos \nu)} \quad (4)$$

Where H is calculated from the equation:

$$\rho_w \frac{\partial H}{\partial t} = -\frac{A_{wet}}{A_t} \dot{m}_w \quad (5)$$

4) Assumptions of this model are

- Condensation considered here is drop-wise.
- During the first stage of evaporation base area of the droplet is constant, and contact angle decreases until the receding value is reached as shown in fig. From this point on, contact angle is preserved and droplet volume reduction yields a wet area decrease.

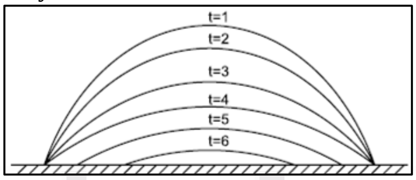

Fig. 2: Droplet shape evolution during evaporation

During condensation, contact angle is assumed constant and a single representative base droplet diameter d is calculated from eqn. (3.1.3). On the other hand, during demist process droplet volume reduction is computed from the height variation and new contact angle is obtained from the geometric relationship as given in following eqn.

$$V = \frac{\pi (d/2)^3}{3(\sin \nu)^3}(1 - \cos \nu)^2 (2 + \cos \nu) \quad (6)$$

Where, $V = \sqrt{3}\, d^2 H / 2$

5) Model equations for air conditioner

a) Energy balance equation for air conditioner

Rate of change of energy inside AC = Heat from the atmosphere + Heat from the cabin - Heat into the cabin- Heat load on the cabin

$$\frac{d}{dt}(V_{ac}\rho_{ac}Cp_{ac}T_{ac}) = Q_s \rho_\infty Cp_\infty T_\infty + (Q_5 - Q_s)\rho_{c5}Cp_{c5}T_{c5} - Q_{in}\rho_{ac}Cp_{in}T_{ac} - \eta_{ac} Capacity_{ac} \quad (7)$$

Humidity in AC is the saturated humidity at AC temperature.

$$\omega = \omega_{sat}\Big|_{T_{ac}} \quad (8)$$

Density of air from AC

$$\rho_{ac} = \rho_a + \rho_v \quad (9)$$

6) Equations for Droplet Diameter and Volume:

Droplet diameter is calculated from the following equation:

$$d = \frac{12\sqrt{3}(\sin \nu)^3 H}{\pi(1 - \cos \nu)^2 (2 + \cos \nu)} \quad (10)$$

a) Geometrical relationship to calculate contact angle:

$$V = \frac{\pi (d/2)^3}{3(\sin \nu)^3}(1 - \cos \nu)^2 (2 + \cos \nu) \quad (11)$$

Where, $V = \sqrt{3}\, d^2 H / 2$

b) Calculation of Area for latent heat transfer:

$$A_g = \Pi\, d^2 / 2 \qquad (12)$$

B. Computational Methodology

The evaluation for performance could be done using CFD software or offering analytical treatment. The effectiveness of the mechanism shall be evident thru' the pictorial representation of the results. The depiction is typically in terms of temperature values and the evenness of its spread over the windshield. Heating coils shall be deployed at the designated locations. The configuration of the system shall be determined in terms of nature of the heating coil, its location and number of turns, rate of heating needed and so on.

Further, for addressing the Product Development phase, the design shall be expedited using a suitable CAD/ CAE solution in the industry while the feasibility of manufacturing using a relatively simple process shall be proposed. Economy in the cost of manufacturing could also be looked into while pursuing the work.

During modeling CATIA V5 tool used for CAD Model preparation. Gambit 2.2.30 interface used for pre-processing. During discretization, quadelement with 2 element size used. Initial boundary conditions are defined in Gambit interface. For Processing and post-processing ANSYS Fluent 14.5 interface used.

1) Heating Coil arranged in horizontal Direction

In this type of arrangement, heating coils are arranged in windshield in horizontal direction. Pitch between two coils is 170 mm. CATIA V5 tool used for modeling. Below diagram shows the overall view of the configuration.

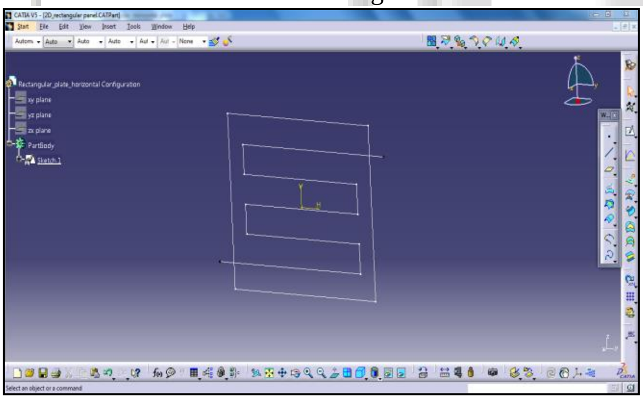

Fig. 3: Heating coil horizontal arrangement in CATIA v5 interface

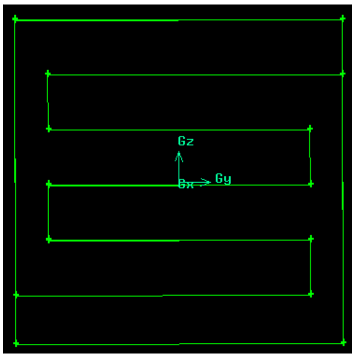

Fig. 4: Heating coil horizontal arrangement in Gambit interface

2) Heating Coil Arranged in Vertical Direction

In this configuration, distance between two coils is 170mm. Vertical configuration is shown in below figure.

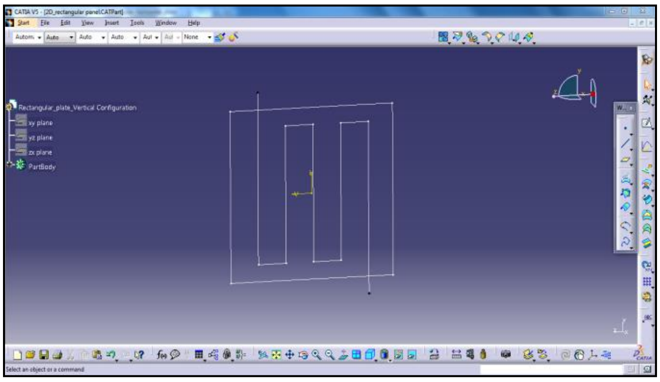

Fig. 5: View of vertical heating coil arrangement

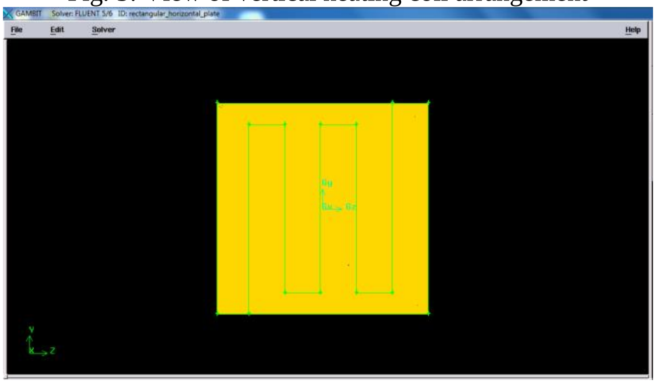

Fig. 6: Meshed model for vertical type heating coil arrangement

3) Heating Coil Arranged in Peripheral Direction:

In this case, nozzles are mounted at the bottom and top side of the glass plate. Hot air will passed through the nozzles.

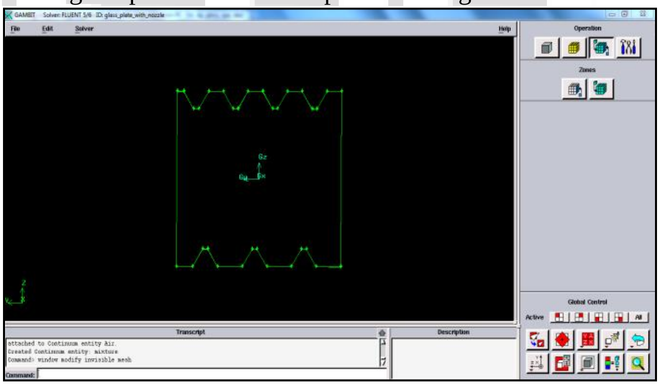

Fig. 7: 3D view of windshield with peripheral heating coil arrangement

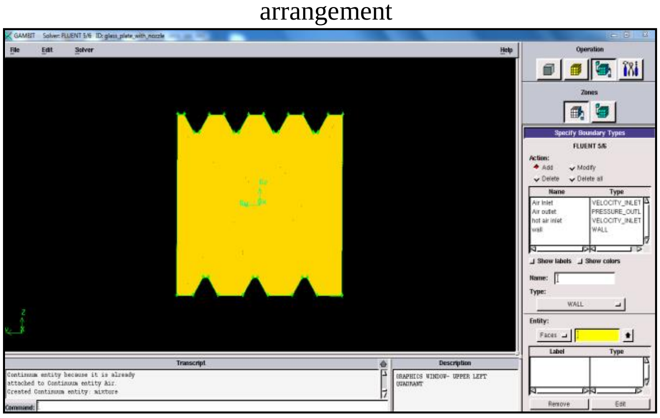

Fig. 8: Meshed Model for peripheral heating coil type arrangement

C. Analysis Results

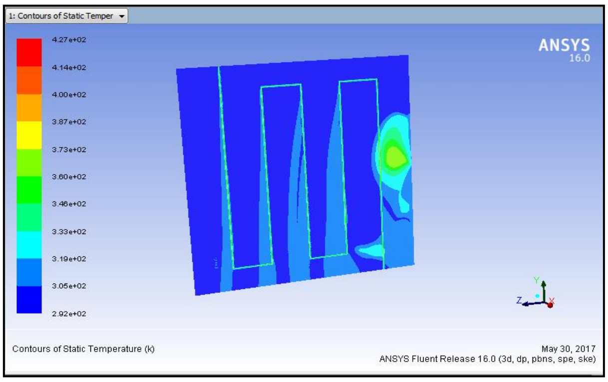

Fig. 9: Temp plot for horizontal heating coil arrangement

In this temp. Plot, left side color strip shows the different temp variation range. Blue color shows the lowest temp while upper color shows the highest temp in the given boundary conditions.

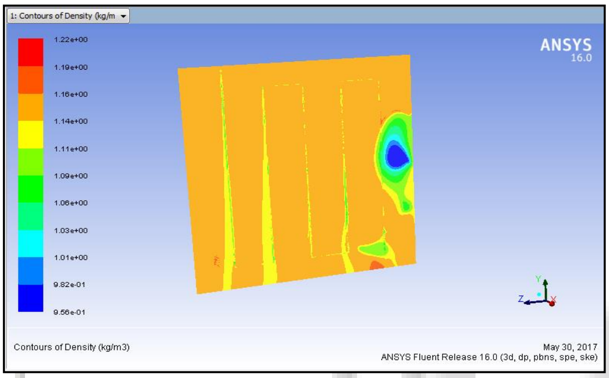

Fig. 10: Density plot for horizontal heating coil arrangement

Fig. shows the density distribution over the process. Blue color shoes the lower density value and as we go up value of density increases. Highest value of density shown in red color.

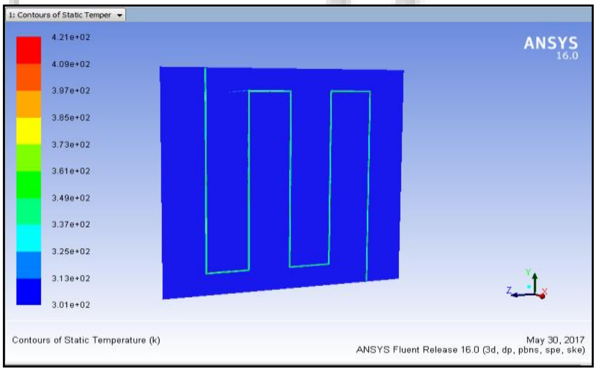

Fig. 11: Density plot for vertical heating coil arrangement.

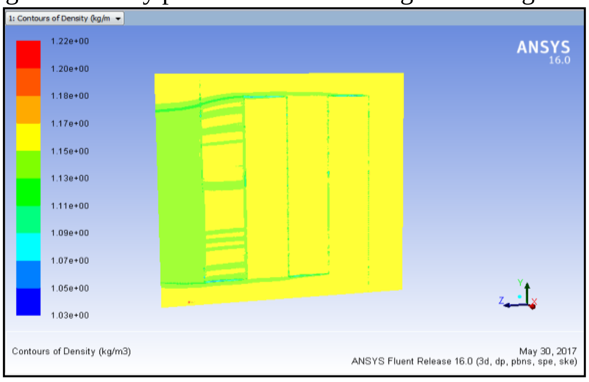

Fig. 12: Density plot for vertical heating coil arrangement.

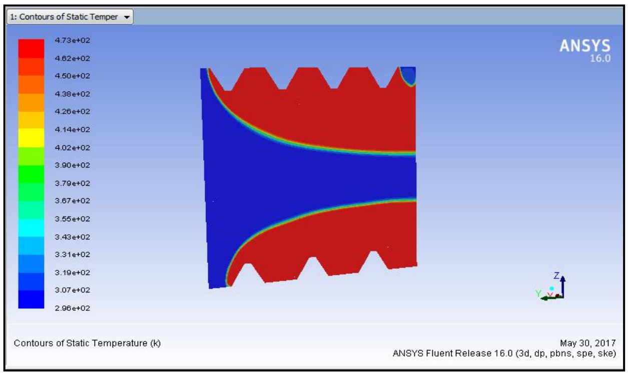

Fig. 13: Temp plot for nozzle inserts configuration

In this type, nozzle type inlets are given at the top and bottom level of glass. Hot air is passed through this nozzle. Temperature plot shows the variation with respected to flow of air.

From different configuration of heating coil over the glass, such as horizontal, vertical and nozzle type inserts, horizontal type configuration shows the better results as compared to vertical type configuration. Hot air passed through nozzle in 3rd configuration. While comparing horizontal and nozzle type configuration; horizontal arrangement of heating coil give more significant result as the uniform distribution of temperature is there.

VI. Observation Table

The temperature values observed for same no of iterations/ time over all three configurations are as follows.

Configuration No.	Configuration Name	Temperature in K
1	Horizontal Heating coil	335
2	Vertical Heating coil	322
3	Nozzle type inserts	330

Table 1: Observation Table:

A. Proposed Analytical Tool used for Product Design and Development: FMEA

1) Failure Modes and Effects Analysis-

Failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service. Failures are prioritized according to how serious their consequences are, how frequently they occur and how easily they can be detected. The purpose of the FMEA is to take actions to eliminate or reduce failures, starting with the highest-priority ones.

Failure modes and effects analysis also documents current knowledge and actions about the risks of failures, for use in continuous improvement. FMEA is used during design to prevent failures. Later it's used for control, before and during ongoing operation of the process. Ideally, FMEA begins during the earliest conceptual stages of design and continues throughout the life of the product or service.

A successful FMEA activity helps identify potential failure modes based on experience with similar products and processes or based on common physics of failure logic. It is widely used in development and manufacturing industries in various phases of the product life cycle. Effects analysis refers to studying the consequences of those failures on different system levels.

Functional analyses are needed as an input to determine correct failure modes, at all system levels, both for functional FMEA or Piece-Part (hardware) FMEA. An FMEA is used to structure Mitigation for Risk reduction based on either failure (mode) effect severity reduction or based on lowering the probability of failure or both. The FMEA is in principle a full inductive (forward logic) analysis, however the failure probability can only be estimated or reduced by understanding the failure mechanism. Ideally this probability shall be lowered to "impossible to occur" by eliminating the (root) causes. It is therefore important to include in the FMEA an appropriate depth of information on the causes of failure (deductive analysis).

The ground rules of each FMEA include a set of project selected procedures; the assumptions on which the analysis is based; the hardware that has been included and excluded from the analysis and the rationale for the exclusions. The ground rules also describe the indenture level of the analysis, the basic hardware status, and the criteria for system and mission success. Every effort should be made to define all ground rules before the FMEA begins; however, the ground rules may be expanded and clarified as the analysis proceeds. A typical set of ground rules (assumptions) follows:

- Only one failure mode exists at a time.
- All inputs (including software commands) to the item being analyzed are present and at nominal values.
- All consumables are present in sufficient quantities.
- Nominal power is available

Major benefits derived from a properly implemented FMEA (or FMECA, criticality analysis) efforts are as follows:

1) It provides a documented method for selecting a design with a high probability of successful operation and safety.
2) A documented uniform method of assessing potential failure mechanisms, failure modes and their impact on system operation, resulting in a list of failure modes ranked according to the seriousness of their system impact and likelihood of occurrence.
3) Early identification of single failure points (SFPS) and system interface problems, which may be critical to mission success and/or safety. They also provide a method of verifying that switching between redundant elements is not jeopardized by postulated single failures.
4) An effective method for evaluating the effect of proposed changes to the design and/or operational procedures on mission success and safety.
5) A basis for in-flight troubleshooting procedures and for locating performance monitoring and fault-detection devices.
6) Criteria for early planning of tests.
7) From the above list, early identifications of SFPS, input to the troubleshooting procedure and locating of performance monitoring / fault detection devices are probably the most important benefits. In addition, these procedures are straightforward and allow orderly evaluation of the design.

For the case of current thesis work, the analysis towards FMEA has been exclusively carried out as below:

Sr. No.	Mode of failure	Cause	Effect	O (Occurrence)	S (Severity)	D (Detection)	RPN (Risk Priority No.)	Remedial / Corrective action	Responsible owner
1	Loosening or disconnection at the junctions or joints	Improper or inadequate fitment or clamps not secured	Overheating at the joints. Circuit not complete resulting into power	4	5	2	40	Secure the joints positively with suitable jonining methods or tools like a	Design Engineer
2	No power output from Battery	Over-use or draining during usage	Heating element unable to generate enough or any	3	8	2	48	Suitable capacity and type of the battery to be	Design Engineer / Maintenance Team
3	Low power for application	Improper selection of the elements of the heating system or improper	Inadequate temperature for vaporizing	2	7	5	70	Recommend suitable configuration of the power supply	Design Engineer
4	Heating element peeling off from the windshield	Improper method of assembly. Inadequate	Functional and Aesthetic compromise leading to	2	5	2	20	Design alternative to be suggested for prevention	Design Engineer
5	Uneven heating over the length of the heating element	Low quality or improper type of heating element chosen	Patches are likely to be visible for the condensate awaiting vaporization	6	6	1	36	Quality assurance for heating element to be reinforced during procurement.	Purchase Officer/ Design

Fig. 2: Analysis towards FMEA

VII. Conclusion

The condensate causes safety concern for the driver while the vision is partly or wholly blocked during driving with high in-cabin tendency to fog or form condensed water particles. The study reveals the mechanism of formation of the condensate over the windshield. The generic methods already in use have been modified with renewed configuration and analysed. New introduction of heating element fitting within the wiper is also proposed. The thesis work attempts to investigate the formation of the condensate on one hand while applying innovative techniques for countering the problem using (i) heating elements over the windshield with the designated configuration (ii) blowing hot air over the windshield from the top and the bottom side of the windshield. The simulation using pre-processor GAMBIT and the solver ANSYS FLUENT certainly seem promising for arriving at a solution. FMEA could stand as a effective tool for predicting failures and aiding the phase of Product Design and Product Development. Results are being documented to substantiate the findings during this work.

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