

Optical Correction for High-Speed Visualization of Two-phase Flow Boiling: Ray Tracing Design and Validation of a Corrective Lens

Rodrigo C. Branco^{1,*}, João S. Pereira¹, José B. Ribeiro¹

1: Univ Coimbra, ADAl, Department of Mechanical Engineering, Rua Luís Reis Santos, Pólo II, 3030-788 Coimbra, Portugal.

* Correspondent author: rodrigo.branco@adai.pt

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ABSTRACT

Understanding heat transfer mechanisms in two-phase flow boiling requires highly accurate, high-speed optical visualization. However, capturing high-quality images in cylindrical systems remains technically challenging due to optical aberrations inherent to the geometry. Depending on the fluid phase, the tube acts either as a convergent optical system under liquid-dominated conditions or as a divergent system under vapor-dominated conditions, leading to non-uniform illumination and loss of crucial structural data near the tube walls. This work presents a systematic approach to correct these distortions by developing an analytical optical model based on a thick-lens ray-tracing matrix method implemented in MATLAB® R2024b. To counteract the convergent effect in liquid-dominated flows, a biconcave divergent lens with a radius of 12.4 mm was designed and positioned between the light source and the tube. Conversely, to address the divergent effect in vapor-dominated flows, a positive meniscus convergent lens was designed and placed between the tube and the camera. Due to geometric constraints, the outer surface of this convergent lens was optimized using regression analysis, yielding an eighth-order polynomial profile. Both corrective elements were fabricated using a cost-effective Creality 3D resin printer and subjected to post-printing curing and polishing. Experimental validation with a high-speed camera at 2000 fps demonstrated significant improvements in image quality across both flow regimes. The divergent lens enabled detailed observation of vapor plugs, slugs, and small bubbles by eliminating central light concentration. The convergent lens effectively mitigated peripheral dark zones under high vapor quality conditions, rendering interfacial flow structures highly visible. Despite minor experimental challenges, such as mechanical alignment and optical magnification of the convergent lens, the results highlight the effectiveness of integrating optical analytical modeling with rapid-prototyping 3D-printed lenses. This approach offers a versatile, low-cost framework for improving visualization accuracy in flow boiling research.

1. Introduction

Understanding heat transfer mechanisms in two-phase flow boiling requires detailed characterization of flow patterns and phase interactions. High-speed optical imaging has become indispensable for this purpose, enabling researchers to identify flow patterns, visualize bubble

dynamics, and correlate flow patterns with local heat transfer behavior. However, in several studies, it can be observed that accurately capturing high-quality images of two-phase flows in cylindrical systems remains technically challenging (Cao et al., 2023; Kaya et al., 2022; Moran et al., 2021).

The fundamental challenge arises from the optical properties of the cylindrical geometry itself. The propagation of light through a glass tube depends strongly on the refractive-index distribution within the flow domain. In liquid-dominated conditions, the curved glass and liquid interfaces can act as a convergent optical system, concentrating light toward the center of the tube while leaving the periphery underexposed. Conversely, under vapor-dominated conditions, the refractive-index contrast may produce the opposite effect, causing the tube to behave as a divergent optical system and altering the spatial distribution of light across the image. These optical aberrations generate uneven illumination and distortions of flow structures, particularly near the tube walls where many of the relevant phase interactions occur. When studying flow boiling phenomena, this limitation is particularly acute, as accurate characterization of interfacial dynamics and flow pattern transitions depends on uniformly high-quality visualization across the entire tube cross-section.

While the optical challenge of cylindrical visualization is well-recognized, systematic approaches to optical correction—particularly through analytical design methods—remain underdeveloped in the literature. This work addresses this gap by applying optical system design principles to a practical two-phase flow visualization problem. Specifically, a matrix method for thick-lens analysis is developed to design and validate corrective optical elements capable of compensating for the optical distortions introduced by glass tubes, achieving substantially improved image quality across different flow regimes.

2. Methodology

To visualize two-phase flow boiling phenomena, an experimental setup was developed based on an open-loop configuration. Water supplied from the grid was fed into a boiler and heated to its boiling point at atmospheric pressure. At the boiler outlet, a horizontal, smooth, circular glass tube was installed to allow optical access to the boiling flow. The glass tube has an outer diameter (D_o [mm]) and an inner (D_i [mm]) diameter of 26 mm and 20 mm, respectively, and its position within the setup is illustrated in Figure. 1. Downstream of the visualization section, a plate heat exchanger was installed to cool the heated fluid. Cooling was provided by a separate water line connected to

the grid, allowing the working fluid to be sufficiently cooled before being safely discharged into the sewage system.

High-resolution images of the flow boiling process were acquired using a Photron Mini UX high-speed camera equipped with a Sigma 105 mm macro lens. Adequate illumination of the test section was ensured by positioning a high-intensity light source aligned with the camera lens. A light diffuser was placed between the light source and the glass tube to provide uniform illumination and to minimize reflections from the curved glass surface.

The initial raw images acquired under different flow conditions, shown in Figure. 2-A and 2-B, exhibited suboptimal image quality due to optical distortions inherent to the cylindrical glass geometry. In the liquid-dominated condition (Figure. 2-A), the curved glass tube acts as a converging optical lens that focuses the incident light toward the tube center. As a result, the central region is excessively illuminated, while the peripheral regions are under-illuminated, leading to the loss of important flow information near the tube walls. In the vapor-dominated condition (Figure. 2-B), although the overall illumination appears more uniform due to the higher vapor content within the tube, image quality remains compromised by non-uniform light distribution across the cross-section. In particular, the regions near the tube walls remain poorly resolved, making it difficult to accurately visualize flow structures and phase interfaces throughout the entire cross-section.



Figure. 1 Two-phase boiling-of-water flow visualization experiment.

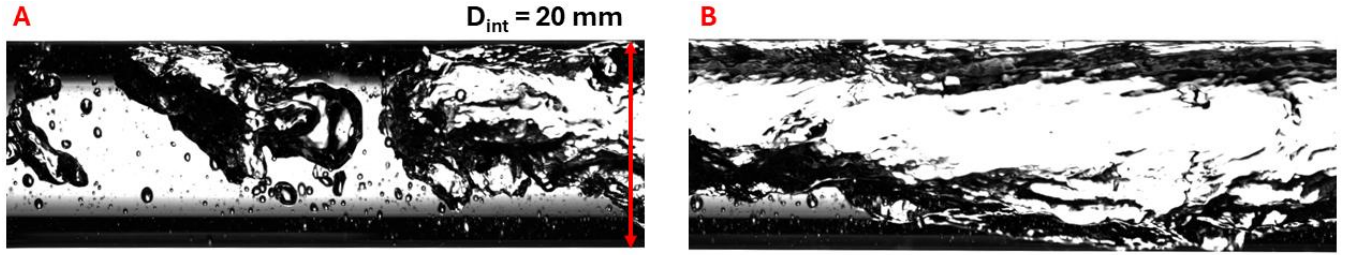


Figure. 2 Raw flow boiling images of water acquired at 2000 fps with a shutter frequency of 20 kHz and a resolution of 1280x720 px, illustrating the optical distortions induced by the cylindrical glass tube: (A) liquid-dominated flow with low vapor quality; (B) vapor-dominated flow with high vapor quality.

2.1 Optical Model

To understand the non-uniform lighting issue, a ray tracing-based optical model of thick lenses (Frank L. Perdrotti et al., 2017) was developed in MATLAB® R2024b. To determine light ray refractions, the rays must be traced from the source to their exit from the water-filled glass tube. As shown in Figure. 3, the calculations consider the sequence of optical interfaces encountered by the light as it propagates through the cylindrical tube. Depending on the prevailing phase (liquid or vapor) within the tube, the refractive-index distribution changes, resulting in different optical behaviours. For the liquid-dominated condition (Figure. 3-A), first, the light transitions from air into the glass tube, which is considered a meniscus lens, before reaching the water.

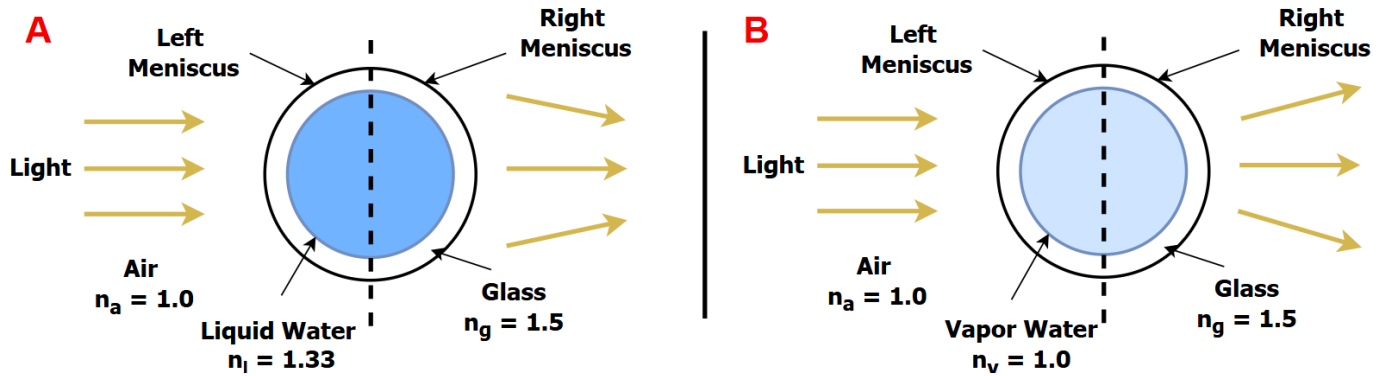


Figure. 3 Schematic illustration of the water-filled glass tube optical interfaces.

Within the tube, the light passes through a column of liquid water, which acts as a second lens. Finally, the light transitions from water back into the glass tube and then into air, forming another meniscus lens. For the liquid-dominated condition (Figure. 3-B), the liquid water is replaced by vapor, and the light passes through air, glass, vapor, glass, and air. Owing to the significantly

lower refractive index of the vapor phase, the optical response of the system changes, modifying the light distribution across the tube cross-section.

Using the thick lenses approach, the matrices for the left meniscus, M_{left} , the water column, M_w , and the right meniscus, M_{right} , are derived, as shown in equations (1)-(3).

$$M_p = \begin{bmatrix} 1 & 0 \\ \frac{n_g - n_w}{n_w R_{int}} & \frac{n_g}{n_w} \end{bmatrix} \times \begin{bmatrix} 1 & t_g \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{n_a - n_g}{n_g R_{ext}} & \frac{n_a}{n_g} \end{bmatrix} \quad (1)$$

$$M_w = \begin{bmatrix} 1 & t_w \\ 0 & 1 \end{bmatrix} \quad (2)$$

$$M_n = \begin{bmatrix} 1 & 0 \\ \frac{n_g - n_a}{n_a (-R_{ext})} & \frac{n_g}{n_a} \end{bmatrix} \times \begin{bmatrix} 1 & t_g \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{n_w - n_g}{n_g (-R_{int})} & \frac{n_w}{n_g} \end{bmatrix} \quad (3)$$

Where, R_{ext} [mm], and R_{int} [mm] are the external and internal radius of the glass tube, respectively, t_a [mm], t_g [mm], and t_w [mm] are the travelling distances of the light rays through the air, glass, and water, respectively, and n_a [-], n_g [-], and n_w [-] are the refraction indexes of air, glass, and liquid-water or vapor, respectively, in which the values are indicated in Figure. 3.

Note that in the present formulation, the internal fluid refractive index n_w accounts for both liquid-water and vapor condition cases. Accordingly, the same optical framework is applied to both regimes, with only the refractive index of the internal medium being modified to represent either liquid (n_l) or vapor (n_v), depending on the flow condition. This allows a unified description of the optical system while capturing the changes in light propagation induced by both cases.

Additionally, the individual matrices are applied sequentially, corresponding to the order in which the optical actions affect the light ray as it traverses the system. Therefore, the ray-transfer matrix for the complete optical system, M_{tot} , is calculated as shown in the equation (4).

$$M_{tot} = M_{right} \times M_w \times M_{left} \quad (4)$$

To determine the position of each ray after passing through the optical interfaces based on the angle α_f [°], and the y coordinate y_f [mm], equation (5) is applied with the condition that each ray that enters in the optical system with a certain height (y_0) with an angle ($\alpha_0 = 0^\circ$) is collimated.

$$\begin{bmatrix} y_f \\ \alpha_f \end{bmatrix} = M_{tot} \times \begin{bmatrix} y_0 \\ \alpha_0 \end{bmatrix} \quad (5)$$

Figure. 4 shows the results of the ray tracing model for both flow conditions. As observed in Figure. 4-A, the liquid-filled glass tube behaves as a converging optical system, concentrating the

incident light toward the center of the tube. Consequently, the central rays are focused toward the imaging region, whereas the rays passing near the upper and lower tube walls are deflected away from the camera field of view. This results in a higher light intensity at the center of the image and reduced illumination near the tube walls, producing the dark peripheral regions observed in the flow boiling images presented in Figure. 2-A.

Conversely, as shown in Figure. 4-B, the vapor-filled glass tube behaves as a diverging optical system. Although the optical behavior is opposite to that of the liquid-filled tube, a similar imaging limitation is observed. In this case, the rays traversing the central region of the tube remain within the camera field of view, while those passing near the upper and lower walls are diverged away from the imaging region. As a result, flow structures located near the tube walls are again poorly illuminated and difficult to visualize, explaining the loss of image quality observed in the vapor-dominated flow images shown in Figure. 2-B.

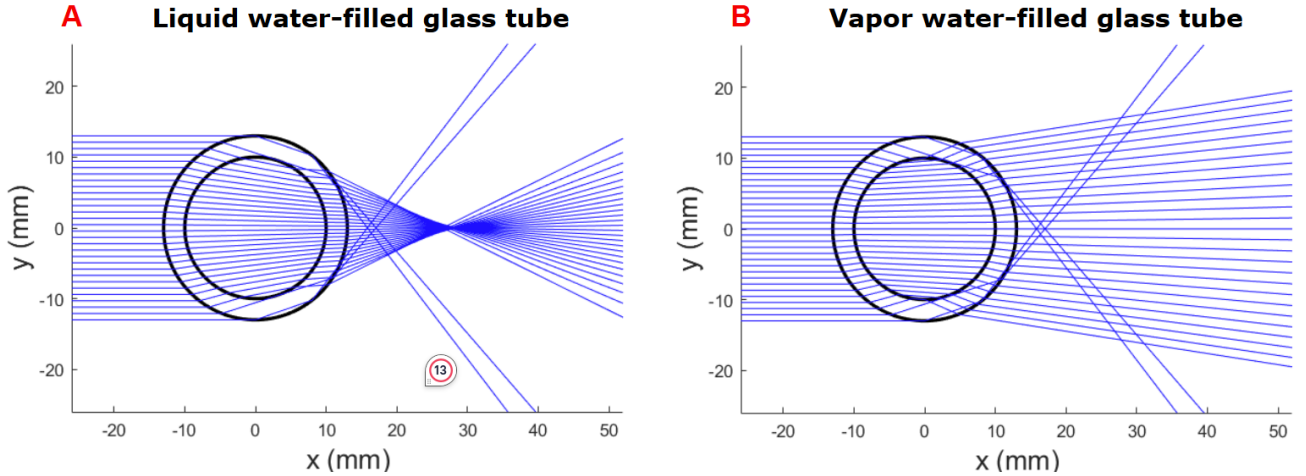


Figure. 4 Ray tracing optical model results of the liquid water-filled glass tube (A) and the vapor water-filled glass tube (B).

Therefore, in order to oppose the convergence observed in Figure. 4-A, a biconcave divergent lens is placed between the light source and the glass tube to counteract this effect. Implementing this solution involves adding the divergent lens matrix (M_{div}) to equation (4), to obtain equation (6).

$$M_{tot} = M_{right} M_w \times M_{left} \times M_{div} \quad (6)$$

Additionally, M_{div} is calculated through equation (7), where R_{div} [mm], is the external radius of the divergent lens, t_{div} [mm] is the light ray travelling distance through the lens, and n_{div} [-] is the refraction index of the lens.

$$M_{div} = \begin{bmatrix} 1 & t_a \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} \frac{1}{n_{div} - n_a} & 0 \\ \frac{n_{div}}{n_a(R_{div})} & \frac{n_{div}}{n_a} \end{bmatrix} \times \begin{bmatrix} 1 & t_{div} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \frac{1}{n_a - n_{div}} & 0 \\ \frac{n_a}{n_{div}(-R_{div})} & \frac{n_a}{n_{div}} \end{bmatrix} \quad (7)$$

Finally, to oppose to the convergence effect, equation (5) is solved under the condition that each ray entering the optical system at a certain height (y_0) with angle ($\alpha_0 = 0^\circ$) remains collimated at the optical system's exit ($y_f = y_0, \alpha_f = \alpha_0$). Using this iterative method with a biconcave divergent lens positioned next to a water-filled glass tube and considering the refraction index of the divergent lens (n_{div}) to be 1.5, R_{div} was found to be 12.4 mm. Figure. 5 shows the results of the ray tracing optical model with the implementation of the divergent lens.

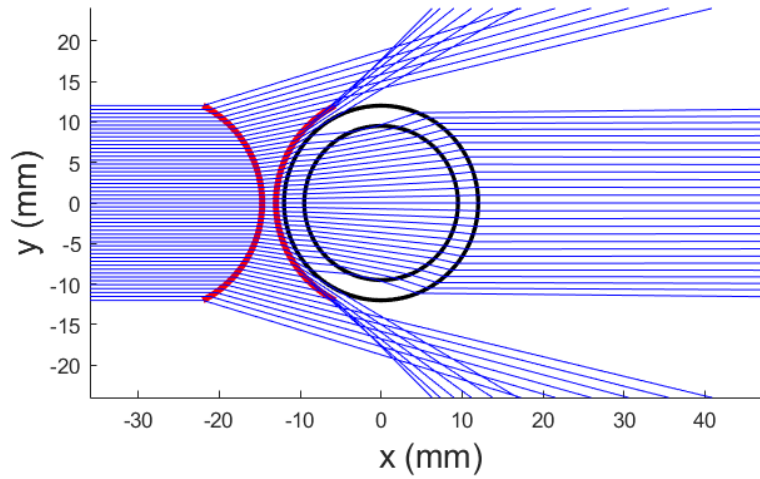


Figure. 5 Ray tracing optical model results with the implementation of the biconcave divergent lens.

On the other hand, to compensate for the diverging optical effect observed in Figure. 4-B, a convergent lens is positioned between the vapor-filled tube and the camera. This placement differs from that adopted for the liquid-filled tube because the objective is to correct a diverging light field generated by the tube itself. If a convergent lens were placed upstream of the tube, part of the incident light would be redirected before reaching the entire tube cross-section, potentially resulting in the loss of flow information. Therefore, the correction can only be effectively applied after the light has traversed the tube and the divergence has been generated. Consequently, the proposed optical correction is implemented by introducing a positive meniscus (convergent lens) matrix (M_{conv}) into equation (4), yielding the modified system matrix given by equation (8).

$$M_{tot} = M_{conv} \times M_{right} M_w \times M_{left} \quad (8)$$

Additionally, M_{conv} is calculated through equation (9), where $R_{conv,left}$ [mm] and $R_{conv,right}$ [mm], are the external radius of the convergent lens left-hand side and right-hand side respectively, t_{conv} [mm] is the light ray travelling distance through the lens, and n_{conv} [-] is the refraction index of the lens.

$$M_{conv} = \begin{bmatrix} 1 & 0 \\ \frac{n_{conv} - n_a}{n_a(-R_{conv,right})} & \frac{n_{conv}}{n_a} \end{bmatrix} \times \begin{bmatrix} 1 & t_{conv} \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ \frac{n_a - n_{conv}}{n_{div}(-R_{conv,left})} & \frac{n_a}{n_{conv}} \end{bmatrix} \times \begin{bmatrix} 1 & t_a \\ 0 & 1 \end{bmatrix} \quad (9)$$

Finally, to oppose the divergent effect of the vapor water-filled tube, equation (5) is solved under the condition that each ray entering the optical system at a certain height (y_0) with angle ($\alpha_0 = 0^\circ$) remains collimated at the optical system's exit ($y_f = y_0$, $\alpha_f = \alpha_0$). Using this iterative method with a positive meniscus lens positioned next to a water-filled glass tube and considering the refraction index of the convergent lens (n_{conv}) to be 1.5, the $R_{conv,left}$ and $R_{conv,right}$ ray tracing model results are shown in Figure. 6.

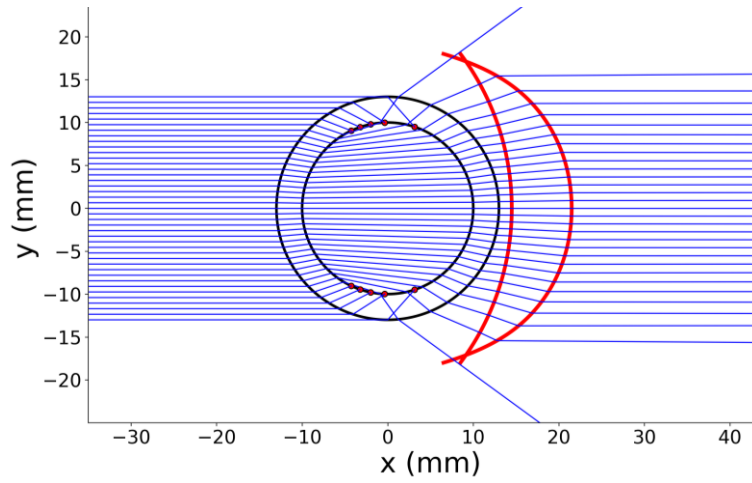


Figure. 6 Ray tracing optical model results with the implementation of the positive meniscus lens.

To compensate for the diverging optical effect produced by the vapor-filled tube, a positive meniscus lens was selected as the corrective optical element. This configuration was chosen because it allows the diverging rays emerging from the tube to be efficiently intercepted and redirected toward the camera. A conventional biconvex lens would not be suitable for this application because its first curved surface would face away from the tube. As a result, the lens would effectively move away from the diverging rays, making it difficult for the upper and lower rays to be captured. In contrast, the positive meniscus geometry, with both curved surfaces facing

the tube, extends the optical surface toward the incoming rays, allowing the diverging rays to be intercepted and redirected while providing the required optical power for correction.

The left-side radius of curvature ($R_{conv,left} = 30$ mm) was selected to ensure that all relevant rays emerging from the tube were intercepted by the corrective lens. Subsequently, the right-side surface was determined such that the rays exiting the optical system were collimated. It was found that a simple circle surface equation could not satisfy this condition over the entire tube cross-section. Therefore, the required surface profile was obtained by independently determining the shape required to collimate each ray and subsequently performing a regression analysis on the resulting coordinates. The resulting profile of $R_{conv,left}$ was found to be best represented by an eighth-order polynomial surface of the form shown in equation (10) with an R-squared (R^2) of 0.999991.

$$x = t_{conv} - 2.51 \times 10^{-2}y^2 - 4.251 \times 10^{-5}y^4 + 1.012 \times 10^{-7}y^6 - 5.272 \times 10^{-10}y^8 \quad (10)$$

Moreover, as observed in Figure. 6, it is important to note that two of the rays are not captured by the corrective lens and are not being collimated. This occurs because, as $R_{conv,left}$ decreases, the rays emerging from the left surface of the lens become more strongly divergent. Consequently, a steeper right-side surface would be required to collimate them. Under these conditions, however, the required curvature becomes geometrically unfeasible, preventing all rays from being simultaneously collimated, as shown in Figure. 7.

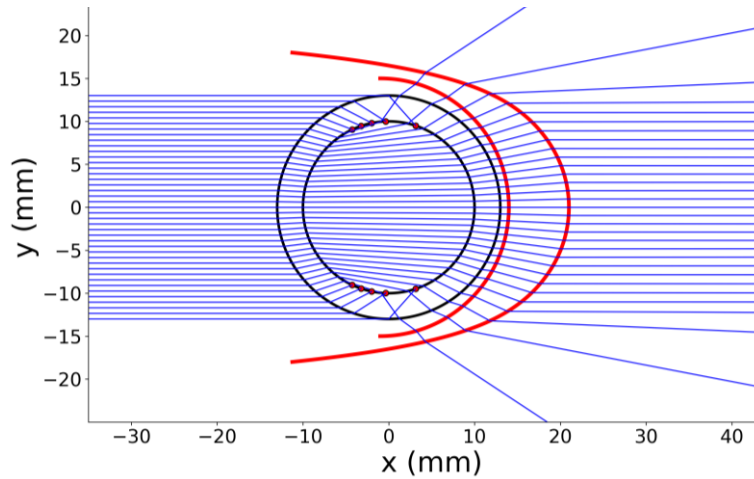


Figure. 7 Ray tracing results for the optical system with the positive meniscus lens, showing the geometric constraint that prevents all diverging rays from being captured and collimated.

2.2 Divergent and convergent lens development

After determining the geometries of the divergent and convergent corrective lenses, as shown in Figure. 8, the components were fabricated using a Creality SKY 3D resin printer and transparent UV-curable resin provided by Creality.

After printing, the lens was fully cured under ultraviolet light and polished to improve its optical quality. To further enhance surface uniformity and transparency, a thin layer of acrylic spray was applied. Moreover, care was taken to maintain a controlled gap between the divergent lens and the glass tube. This gap was assumed to be 1 mm in the optical calculations and was necessary to prevent thermal damage to the lens surface caused by the glass tube's external wall reaching a temperature of approximately 100 °C.

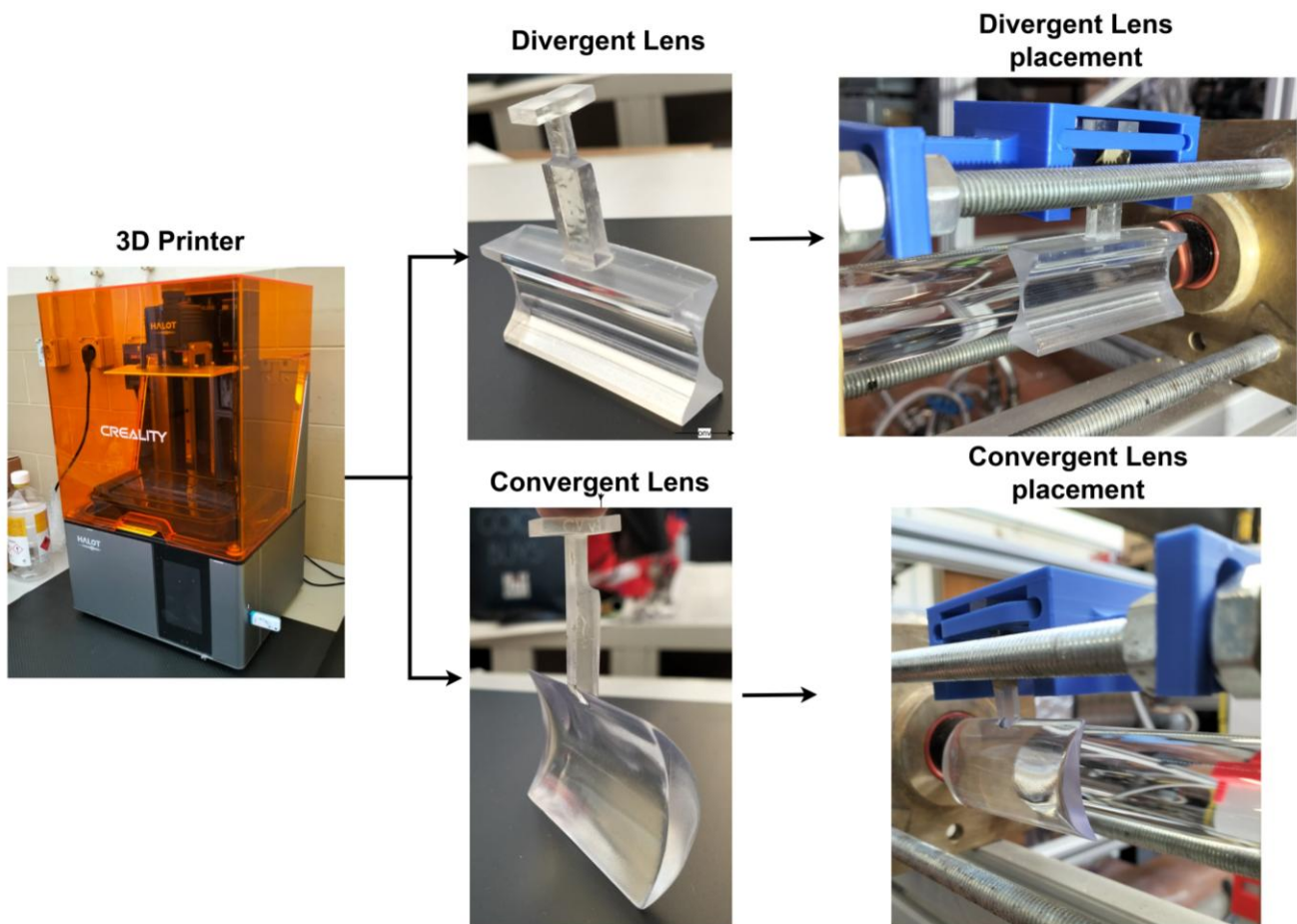


Figure. 8 Pictures of the 3D lens development.

3. Results and Discussion

Figure. 9-A and 9-B display the images captured using the divergent lens at different shutter speeds. The lens prevents light from concentrating in the middle of the glass tube, which makes

the large vapor plugs and slugs visible, as well as the smaller bubbles with great detail. These results demonstrate the strong potential of the proposed optical approach.

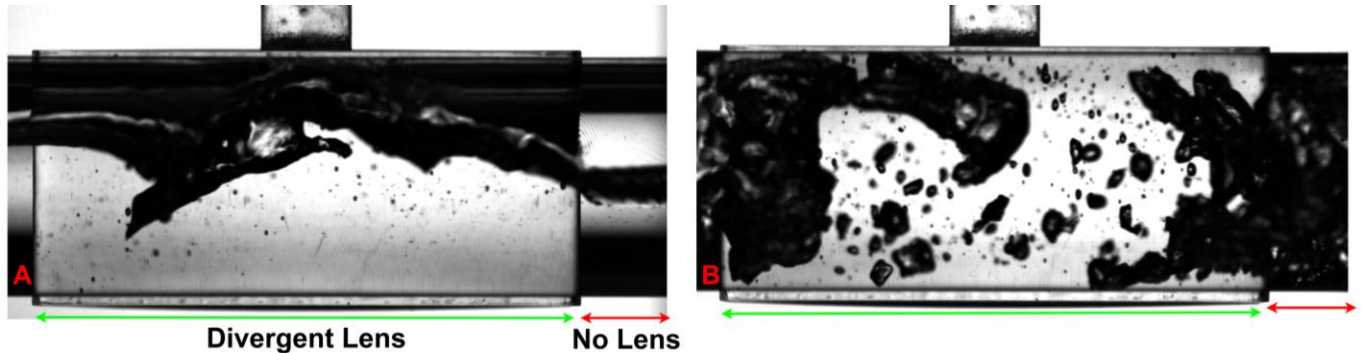


Figure. 9 Flow boiling of water images captured at 2000 fps, shutter frequency of 32 kHz and 1280x720px (A), and at 2000 fps, shutter frequency of 25 kHz and 1280x720px (B) with a resin biconcave divergent lens.

Some very small portions near the top and bottom of the tube remain partially obscured in certain regions of the images. Apart from the lens curvature radius, which can be further refined, this effect is also primarily attributed to the lens positioning. Achieving and maintaining a uniform and optimal distance between the lens and the glass tube represents the main experimental challenge. Further improvements could be achieved through iterative refinements, including optimization of the 3D printing parameters, better polishing procedures, and more uniform application of the acrylic coating (Branco et al., 2025).

Some gray regions are also observed in the images, which may be associated with surface non-uniformities or internal irregularities inherent to the resin-based printing process.

Regarding the images captured with the convergent lens, shown in Figure. 10-A and 10-B, a clear improvement in illumination is observed. In particular, for high vapor quality conditions, the flow structures become significantly more visible, with the dark regions caused by the optical divergence of the vapor water-filled glass tube almost eliminated.

Nevertheless, some limitations can be identified. In one of the cases, the lens is slightly tilted and not properly aligned due to insufficient mechanical support, as the lens mass exceeded the rigidity of the mounting system. In addition, the contact region between the support and the lens introduces additional optical disturbances, which prevent the system from achieving fully uniform image quality.

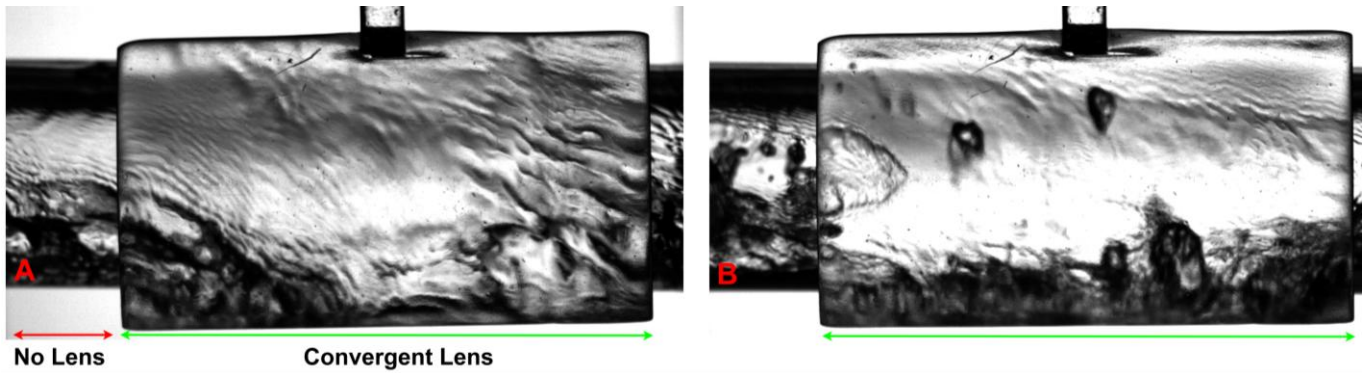


Figure. 10 Flow boiling of water images captured at 2000 fps, shutter frequency of 32 kHz and 1280x720px (A), and at 2000 fps, shutter frequency of 25 kHz and 1280x720px (B) with a resin positive meniscus convergent lens.

Another relevant effect is the apparent magnification of the flow boiling images, resulting from the fact that the corrective lens diameter is larger than the tube diameter. This introduces a scaling effect in the recorded images. If this magnification is not desired, two possible approaches can be considered. The first consists of quantifying the optical magnification and rescaling the images to recover the original spatial dimensions. The second involves implementing a dual-lens system in which the optical path is re-collimated after correction, ensuring that the final rays exit the system with a field of view matched to the tube diameter.

Despite these limitations, the preliminary results demonstrate the effectiveness of the convergent corrective lens in substantially improving the visualization of flow patterns under high vapor quality conditions.

Moreover, these results show that the use of 3D-printed resin lenses offers a highly cost-effective alternative to custom-manufactured glass lenses with optimized geometries. This approach is particularly attractive for experimental applications that benefit from rapid prototyping and iterative optical design.

4. Conclusions

In many two-phase flow boiling studies, the captured images are of suboptimal quality, exhibiting pronounced light distortions and poor visibility of near-wall structures. Motivated by these recurring issues, an experiment was conducted to investigate the source of these distortions by visualizing the flow boiling of water in a horizontal glass tube. The investigation confirmed that the optical behaviour of the cylindrical geometry depends heavily on the internal phase distribution: the liquid-filled tube acts as a convergent lens that concentrates light centrally, while the vapor-filled tube acts as a divergent lens that scatters light away from the imaging system.

To resolve these limitations, an optical model based on thick-lens ray tracing was developed to characterize both flow regimes. Guided by insights from this model, two customized, cost-effective 3D-printed resin lenses were successfully designed, fabricated, and validated. A biconcave divergent lens was implemented upstream of the test section to counteract the liquid-dominated convergent effect, significantly enhancing illumination uniformity and enabling the detailed capture of bubble dynamics, plugs, and slugs. For vapor-dominated conditions, a positive meniscus convergent lens featuring an analytically derived eighth-order polynomial surface was placed downstream to intercept and correct the diverging light field, effectively eliminating peripheral dark zones and uncovering complex interfacial structures under high vapor quality conditions.

While both resin lenses demonstrated strong potential, their implementation highlighted practical challenges, including surface and internal irregularities from the printing process, the need for precise micro-positioning, and mechanical alignment constraints due to lens weight exceeding the mounting system's rigidity. Additionally, the convergent lens introduced an optical magnification effect that requires spatial rescaling or a dual-lens re-collimation configuration in future work. Despite these challenges, this study successfully demonstrates that combining analytical optical modeling with iterative 3D-printed prototyping provides a powerful, highly adaptable, and accessible methodology for overcoming geometric aberrations, ultimately contributing to more reliable and accurate experimental investigations in two-phase flow boiling research.

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References

- Branco, R. C., Pereira, J. S., & Ribeiro, J. B. (2025). An Experimental Setup to Validate Flow Boiling Heat Transfer Correlations in Horizontal Circular Tubes. *Proceedings of the World Congress on Momentum, Heat and Mass Transfer*. <https://doi.org/10.11159/icmfht25.132>
- Cao, S., Wang, G., Yang, H., Zhao, L., & Guo, H. (2023). R245fa flow boiling heat transfer in a sintering and electroplating modulated tube. *Applied Thermal Engineering*, 219. <https://doi.org/10.1016/j.applthermaleng.2022.119459>
- Frank L. Pedrotti, S. J., Leno M. Pedrotti, & Leno S. Pedrotti. (2017). *Introduction to Optics* (Third Edition, 18, pp. 396–418). Cambridge University Press. <https://doi.org/10.1017/9781108552493>
- Kaya, A., Lecompte, S., & De Paepe, M. (2022). Experimental Flow Boiling Study of R245fa at High Reduced Pressures in a Large Diameter Horizontal Tube. *Energies*, 15(3). <https://doi.org/10.3390/en15030864>
- Moran, H. R., Zogg, D., Voulgaropoulos, V., Van den Bergh, W. J., Dirker, J., Meyer, J. P., Matar, O. K., & Markides, C. N. (2021). An experimental study of the thermohydraulic characteristics of flow boiling in horizontal pipes: Linking spatiotemporally resolved and integral measurements. *Applied Thermal Engineering*, 194. <https://doi.org/10.1016/j.applthermaleng.2021.117085>