Effect of argon concentration on thermal efficiency of gas-filled insulating glass flat-plate collectors

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Abstract: Insulating glass flat-plate collectors can save cost by being produced quickly and automatically in insulated glass production facilities, and they can be filled with argon to reduce heat loss. During its lifetime, the collector is likely to lose argon because of gradual material degradation of the sealing. However, information on the influence of the argon concentration on the collector efficiency is limited. Therefore, the objective of this research work was to analyse this effect. A theoretical material property calculation of argon-air mixtures was carried out to determine the convective losses with variable argon concentrations. Thermal collector performance was measured experimentally using an outdoor solar tracker test rig. The results strongly suggest, that the influence of argon concentration on both the convective losses and the thermal efficiency is non-linear. The measurements revealed that an argon concentration of 90 % can increase average thermal performance by 6.7 $\pm$ 4.8 percentage points. An increase in argon concentration from 0 % to 50 % has almost twice the effect on average thermal efficiency as an increase from 50 % to 90 %. Concluding from these results, an argon leakage threshold of 2.5 percentage points per year is proposed to avoid disproportionate loss of efficiency over time.

Keywords: insulating glass, flat-plate collector, argon, gas concentration, efficiency measurement, convective heat transfer

1 Introduction

1.1 Insulating glass flat-plate collectors

In the last decades, solar thermal systems have been increasingly built as large-scale plants. Depending on the plant size, the system typically consists of several hundreds, up to thousands of square metres of ground-mounted flat-plate collectors (FPCs) [1]. Economies of scale and low specific installation cost make large-scale plants more cost-effective than small-scale, roof-mounted systems [2]. To promote the construction of large-scale plants, Denmark and Germany introduced subsidy schemes which turned out to be mayor success factors for market growth [3]. However, Denmark has recently changed its funding policy by privileging large heat pumps. As a result, the solar district heating market collapsed in 2020. [3] The need for funding schemes shows a remaining demand for cost reductions in the solar thermal heating sector.

To lower the cost of heat generation from solar thermal systems, a reduction in expenses or an increase in performance becomes necessary. A recent design approach to achieve cost reduction for large-scale collector fields is insulating glass flat-plate collectors (IGFPCs). This concept utilizes the production facilities of insulating glass units (IGUs) manufacturers in order to produce solar thermal flat-plate collectors. This design differs significantly from existing methods for performance enhancement with IGUs, where double-glazed front covers are used to insulate conventional collectors. For the latter, the absorber is surrounded by air. This is not the case for IGFPCs, but instead the absorber is surrounded by argon. This allows for further exploitation of loss reduction through the enhanced thermal properties of argon.

The production of flat-plate collectors with IGU machines has been introduced [4] and analysed [5] with respect to its cost. The material costs of the IGFPCs were found to be 91 €/m² and therefore higher than for a conventional reference collector, which was 86 €/m². However, due to the capability of fast production, the novel design and production technique can achieve an overall production cost reduction of 5 % to 11 % [5]. The fast and highly automated assembly process of IGFPCs has therefore a positive effect on the production cost as less time as fewer manual work is needed [4]. Moreover, IGU production is available all over the world. For this reason, production sites without additional investment in machinery or logistics seem to be more cost efficient for IGFPC production.

As described, IGFPCs are produced in a very similar way as IGUs. This makes the collector gas-tight and allows for inert gas fillings. Hence, IGFPCs are considered as gas-filled FPCs. Argon fillings are state-of-the-art for IGUs to increase the insulating effect of the glazing. The latter is due to an approximate 33 % lower thermal conductivity of argon compared to air [6]. Similarly, an IGFPC that is argon-filled instead of air-filled has lower thermal losses and higher thermal efficiency. As a result, argon fillings are promising for performance increase while keeping material costs for collector production acceptable. This has been shown by several investigations and is described in more detail in Section 1.2.

The lifetime of solar thermal systems is typically 20 years or more. The collector field must withstand environmental exposure to maintain its thermal and mechanical properties. For IGFPCs, this means that the argon concentration should be kept as high as possible to maintain the initial thermal performance of the system. However, it is unlikely that this concentration will remain close to 100 % over 20 years or more. Despite the positive effects of argon filling on the collector efficiency, the collector will lose argon during its lifetime due to material degradation of the sealing. This implies a gradual reduction of argon concentration inside the collector. Consequently, the collector will be filled with an argon-air mixture that has inferior thermal properties compared to pure argon. Both the properties of the gas mixture and its influence on the collector efficiency are of interest for further development and research on IGPFCs. To provide an overview of the relevant literature in that specific field, the current state of research will be presented in the following section.

1.2 Performance measurements of gas-filled flat-plate collectors

Argon was not the only gas to be considered for gas-filled FPCs. Other inert gases such as krypton have lower thermal conductivity than argon and are also used for IGU production. However, krypton is more expensive and leads to longer payback times for IGU installations [7]. This resulted in an argon-filled glazing dominance in the IGU market.

The effect of different gases on the efficiency of gas-filled FPCs was investigated by Vestlund et al. [8] using a numerical modelling approach. The authors compared the efficiencies of collectors filled with argon, xenon, krypton, carbon dioxide, and air. For all investigations a gas concentration of $c = 100\ \%$ was assumed. It was shown that inert gas can reduce overall heat losses by up to 20 % (when xenon is used). In his research work, Vestlund [9] concluded that the usage of argon in combination with aluminium absorbers is particularly cost-effective. As stated in section 1.1, the cost-effective design for FPCs is particularly relevant for a reduction of heat generation cost. Therefore, the research in this study focusses on an argon-filled IGFPC using aluminium absorbers.

From the former investigation [8] we can furthermore conclude that the efficiency of an argon-filled collector is 2.6 percentage points[1] higher than for an air-filled collector. This increase was observed for a collector temperature level of $T_{red} = 0.05\ \mathrm{m^2K/W}$. As a result, the effect of concentration on efficiency is likely to range from 0 to 2.6 percentage points for this temperature level.

A similar effect was observed by investigations of Riess et al. [10] who investigated on IGFPCs and determined the thermal efficiency of these modules. Their simulation model showed an increase in efficiency of 4.3 percentage points when argon is used instead of air at a collector temperature level of $T_{red} = 0.05\ \mathrm{m^2K/W}$.

The presented research activities set the range in which the collector efficiency is likely to be affected by substituting air with argon. We note that the use of argon can increase the performance of gas-filled FPCs by up to 2.6 to 4.3 percentage points at $T_{red} = 0.05\ \mathrm{m^2K/W}$. For IGFPC production, this underlines the importance of a reliable high-percentage argon filling to fully utilize the cost-effective production concept [cf. 4].

1.3 Research gap and objective

Former investigations of the thermal performance of argon-filled FPCs have established the limits in which argon affects the collector efficiency. However, in practice, an argon concentration of $c = 0\ \%$ is undesirable and $c = 100\ \%$ is unlikely to be achieved over a life time of 20 years or more. Leakage will occur, and therefore, a mixture of argon and air needs to be considered for a long-term performance evaluation. The effect of argon on the efficiency of IGFPCs has neither been described for $0\ \% < c < 100\ \%$ nor has been validated experimentally.

Hence, the objective of this research was to determine the effect of the argon concentration on the efficiency of IGFPCs. For that, theoretical analyses based on the material properties of argon-air mixtures have been conducted. Subsequently, IGFPC prototypes were experimentally examined using a solar thermal outdoor test rig. In the following section, the selected methodological approach, the IGFPC prototype design, the experimental setup, and the theoretical investigation are described.

2 Methodology for experimental and theoretical investigations

2.1 Methodological approach

The methodological procedure for this research is presented in Figure 1. A theoretical analysis was performed to assess the effect of argon concentration on the collector losses, and an experimental

[1] The distinction between '%' and 'percentage points' was used intentionally, in order to be specific about absolute and relative percentage differences.

analysis was carried out to outline the influence on the collector efficiency. Three steps were taken for the theoretical investigation. As the gas mixture is in contact with the absorber of the collector, the convective heat transfer between the absorber and its surroundings is relevant for the efficiency. Therefore, the effect of argon concentration on this heat transfer was examined. First, the material properties of argon-air-mixtures were computed based on the kinetic gas theory. Second, the convective heat transfer coefficient was derived from that. Given these results, the effect of argon concentration on the collector heat losses was assesed.

The experimental investigation consisted of six steps and began with the production of two IGFPC prototypes with different argon concentration levels. Their argon concentration was measured before and after the thermal performance tests. To obtain a third concentration level for the performance test, one of the modules was refilled. The results were then combined with the theoretical findings to decribe the effect of argon concentration on the efficiency of IGFPCs.

Before the theoretical and experimental procedures are described in more detail, the following section will outline and explain the design of the IGFPC, first.

2.2 Tested prototype collectors

The tested prototypes were double-glazed IGFPCs which were presented in former studies [11–13]. In Figure 2, the schematic structure of one module is shown. The collector is designed for water-based applications. Its distinctive feature is that the absorber is placed inside the IGU and therefore fully surrounded by the filling gas (argon in this case). In that way, costly aluminium casing and solid insulation materials can be replaced with a rear glass cover. The inlet and outlet tubes are shown along with arrows which indicate the fluid flow of the roll-bond absorber. Small spacing elements ensure that the absorber is kept in its position. Furthermore, these spacers provide mechanical stability to the assembly by connecting the front and rear glass panes. The inter-pane cavity is sealed with an edge compound in the same manner as conventional IGUs are sealed. On the front side of the absorber, low-reflective solar glass was used. On the rear side, toughened safety glass with no special coating completes the design. The key dimensions of the collector that were relevant for this study are listed in Table A.1.

The argon concentration plays an important role for insulating glass flat-plate collectors as the thermal characteristics of the filling gas have an impact on its thermal performance. In contrast to conventional flat-plate collectors, IGFPCs have no rear insulating material and therefore convective losses can occur at the front and back side of the collector. Additionally, radiative losses occur at both sides, underlining the importance of a filling gas with low thermal conductivity.

Argon is an inert gas which is widely used for insulating glass units to reduce the heat transfer between the interior of buildings and the environment. It is cheaper than krypton or xenon [14] but has lower thermal conductivity than air [6]. For the production process, the argon concentration is a key indicator to ensure the quality of the produced units and should be between 95 % and 100 %.

2.3 Experimental test procedure

Two collector modules (C_1 and C_2) have been assembled for the experimental tests. The test procedure was conducted as described in Section 2.1. The argon concentration was measured using a handheld device from the fabricator Helantec (type ‘GAS-TESTER’) with a measurement uncertainty of ± 1 percentage points. This gas tester uses an invasive type of measurement where the edge seal of the collector module is penetrated. Due to this measurement constraint, the concentration was measured shortly before and after each performance test to reduce potential leakage from leaving a measurement probe throughout the test.

Both collectors were tested on an outdoor solar thermal test rig (cf. Figure 3), which allows steady-state measurements. A solar tracker ensured that direct solar radiation hit the collector surface perpendicularly. The hydraulic setup was chosen as depicted in Figure 4 and the thermal performance was measured according to the requirements of ISO 9806. Five temperature levels were tested under steady conditions to derive the collector performance constants η_0, a_1 and a_2 using a polynomial regression model.

The power $\dot{Q}$ of the solar collector was calculated according to the ISO 9806 steady-state equation as:

$$\dot{Q} = A_{coll}(\eta_0 G - a_1(T_m - T_a) - a_2(T_m - T_a)^2) \qquad \text{Eq. (1)}$$

where
A_{coll}: Gross collector area in m^2
η_0: Peak efficiency of the collector / optical efficiency
G: Solar irradiance in $\mathrm{W\ m^{-2}}$
a_1: Heat transfer coefficient of the collector / linear heat loss coefficient in $\mathrm{W\ m^{-2}K^{-1}}$
a_2: Temperature-dependent heat transfer coefficient / quadratic heat loss coefficient in $\mathrm{W\ m^{-2}K^{-2}}$
T_m: Average temperature of the heat transfer fluid / mean collector temperature in K
T_a: Ambient air temperature in K

After the first performance test, the collectors were refilled with argon to reach a concentration of 100 % inside the modules. For this refill, two holes had to be drilled inside each polymeric edge seal of the prototypes. Polymeric tubes were fed through to allow the argon to flow in and the residual air to flow out. In this way, the air inside the collector was displaced by the inflowing argon. The latter was fed in by a gas bottle and a pressure reducing valve. By drilling holes in the edge seal, the long-term gas tightness of the modules could no longer be maintained. However, the loss was reduced to a minimum by using butyl mass at the feed-through of the tubes.

After refilling the collectors, a second performance test was conducted to observe differences in collector efficiency. The collectors were tested in the same procedure as before the argon refilling was conducted.

2.4 Theoretical investigation

2.4.1 Computation of material properties

The properties of an argon-air mixture were calculated using equations from kinetic gas theory. Both of the separate gases argon and air, and the mixture of them were treated as ideal gases. Table 1 shows the parameter values which were used for the computation [15].

As a result, the viscosity $\tilde{\eta}$, density ρ, heat capacity c_p and thermal conductivity λ were obtained with dependence on the pressure and temperature of the gas by using the kinetic gas theory, as described in the following.

The density can be expressed by using ideal gas law as:

$$\rho = \frac{p}{\frac{R}{M}T_{gas}} \qquad \text{Eq. (2)}$$

where
p: Gas pressure in Pa
R: Ideal gas constant in $\mathrm{J\ mol^{-1}\ K^{-1}}$
M: Molar mass in $\mathrm{kg\ mol^{-1}}$
T_{gas}: Gas temperature in K

The term for computing the viscosity can be written as [15]:

$$\tilde{\eta} = \frac{26.69\sqrt{MT_{gas}}}{\sigma^2\Omega} \qquad \text{Eq. (3)}$$

where Ω is the so-called collision integral for which Neufeld et al. [16] proposed this empirical equation:

$$\Omega = [A(T^*)^{-B}] + C[\exp(-DT^*)] + E[\exp(-FT^*)] \qquad \text{Eq. (4)}$$

where $T^* = \frac{k_B T_{gas}}{\varepsilon}$, $A = 1.16145$, $B = 0.14874$, $C = 0.52487$, $D = 0.77320$, $E = 2.16178$, and $F = 2.43787$.

The heat capacity is needed for the computation of the thermal conductivity and is derived from kinetic gas theory:

$$c_p = 0.5\frac{R}{M}(f+2) \qquad \text{Eq. (5)}$$

Resulting from the gas properties c_p and $\tilde{\eta}$, the thermal conductivity can be written as:

$$\lambda = \frac{15}{4}\frac{R}{M}\tilde{\eta}\left(\frac{4}{15}\frac{c_p M}{R} + \frac{1}{3}\right) \qquad \text{Eq. (6)}$$

To compute the thermal conductivity of the argon-air mixture, the conductivity for each gas can be computed individually and following that, the mixing rule from Wassiljeva [17], Mason and Saxena [18] and Wilke [19] can be applied. It is expressed as:

$$\lambda_{mix} = \sum_i \frac{c_i \lambda_i}{\sum_j c_j F_{ij}} \qquad \text{Eq. (7)}$$

where

$$F_{ij} = \frac{\left[1 + \sqrt[4]{\frac{M_j}{M_i}}\sqrt{\frac{\tilde{\eta}_i}{\tilde{\eta}_j}}\right]^2}{\sqrt{8\left(1 + \frac{M_i}{M_j}\right)}} \qquad \text{Eq. (8)}$$

and
c: Concentration of a substance within the gaseous mixture
i, j: Indices for the substances in the gaseous mixture

The same applies for the computation of the viscosity of gas mixtures [19]:

$$\tilde{\eta}_{mix} = \sum_i \frac{c_i \tilde{\eta}_i}{\sum_j c_j F_{ij}} \qquad \text{Eq. (9)}$$

For the heat capacity, the following term was used [6]

$$c_{p,mix} = \sum_i c_i \, c_{p,i} \qquad \text{Eq. (10)}$$

where

$$M_{mix} = \sum_i c_i M_i \qquad \text{Eq. (11)}$$

$$w_i = \frac{c_i M_i}{M_{mix}} \qquad \text{Eq. (12)}$$

w: Mass fraction of a substance in the mixture

For the computation of the density of the gas mixture, Amagat's law was used:

$$\rho_{mix} = \left(\sum_i \frac{w_i}{\rho_i}\right)^{-1} \qquad \text{Eq. (13)}$$

2.4.2 Computation of convective heat transfer and collector losses

To assess the impact of the material properties of argon-air-mixtures on the performance of IGFPCs, the convective heat transfer coefficient was calculated. In the literature, numerous empirical equations exist that describe the heat transfer across the gap between the absorber and glass cover. This study adopts the Nusselt correlations from Summ et al. [13] to compute the heat transfer coefficient h with the definition of Nusselt number because this set of equations was particularly derived for IGFPCs:

$h = Nu\, \lambda_{mix} \,/\, d$ Eq. (14)

d: Distance between absorber and front cover (see Table 1)
Nu: Nusselt number

Therefore, a change in the convective heat transfer coefficient will affect the heat flux across the gas-filled cavity of the collector $\dot{Q}_{conv}$ as:

$\dot{Q}_{conv} = \bar{h}\, A_{abs}\, (T_{abs} - T_{gas})$ Eq. (15)

A_{abs}: Area of the absorber
T_{abs}: Temperature of the absorber

where the average heat transfer coefficient $\bar{h}$ will be computed as the arithmetic mean for the front (h_f) and back side (h_b) of the collector.

$\bar{h} = 0.5\, (h_f + h_b)$ Eq. (16)

The total power output of the collectors was measured as described in Section 2.3 and compared to the convective losses, which were computed according to Eq 15. In this study, the term 'convective losses' indicates the heat losses due to convection between the absorber and the front and back cover. It is not including convective losses at the outer surfaces of the collector.

3 Results

When the thermal properties of argon are compared with those of air, it shows that when air is replaced with argon in an IGFPC, the thermal conductivity is reduced by approximately a third. The prior investigations by Vestlund et al. [8] and Riess et al. [10] have shown that this significantly affects the performance of the collectors. In the following sections, theoretical and experimental results will be presented to determine this effect also for argon concentrations in the range of $0\,\% < c_{ar} < 100\,\%$.

3.1 Thermal conductivity and convective heat transfer coefficient computation

The equations from kinetic gas theory described in Section 2.4.1 were used to compute the thermal conductivity λ_{mix} of argon-air mixtures of different mixing ratios and concentration levels, respectively. Additionally, the average heat transfer coefficient $\bar{h}$ was computed according to Eq. 16. Both results are shown in Figure 5 for exemplary parameters.

On the left axis, the influence of the argon concentration c_{ar} on the thermal conductivity of the gas mixture λ_{mix} is shown. The relation between them is to a small extent non-linear. However, as seen in Section 2.4.1, this curve is dependent on the temperature and therefore depends on the operating point of the collector. Therefore, in Section 3.3 the values were computed for the operating points measured within the experimental collector tests, to show the influence of several temperature levels.

The right axis is assigned to the heat transfer coefficient $\bar{h}$. Similar to the curve for λ_{mix}, the heat transfer coefficient shows a non-linear relation to c_{ar}, which confirms the investigations from Asphaug et al. [20] who investigated this effect for double-glazed IGUs. For the chosen parameter set, $\bar{h}$ is reduced by up to 26.6 % when argon is filled inside the collector instead of air.

3.2 Measurement of argon concentration

Argon concentration within the gas-filled cavity of the IGFPC prototypes was measured as described in Section 2.3. The percentages of argon within the gas mixture of the modules C_1 and C_2 are presented in Table 2.

Both collectors have been produced in the same way and the design of both prototypes was identical. However, collector C_2 was not filled with argon, while collector C_1 was approximately half-filled with argon. The performance was then measured after the assembly. After the first test, the concentration was measured again; however, no change was observed for both collectors. This shows that the edge seal of C_1 was working as expected.

During the collector C_1 refilling process, the pressure inside the module increased erratically, leading to a burst of the front cover. As a consequence, C_1 could not be used for further performance tests. The refilling was then repeated for C_2 using larger holes in the edge seal compound to avoid overpressure and reduce the flow resistance for the gas leaving the collector. By changing the refilling method, collector C_2 remained intact; however, the larger drill holes in the edge seal led to an argon leakage during the test. For the second performance test, the collector was refilled with the highest possible argon concentration which was $c_{ar} = 98.7$ %. After the second performance test, the concentration was measured again and amounted to $c_{ar} = 81.9$ %. Two days after the second performance test a further drop to $c_{ar} = 53.0$ % was observed.

Undamaged IGFPCs (or IGUs) normally show significantly lower argon losses as demonstrated by mid-term durability tests from Giovannetti and Kirchner [21]. During these outdoor experiments, three IGFPC prototypes were observed for approx. one year. In that study, the maximum concentration drop amounted to 8 percentage points. This suggests that, the decrease observed in this study of 16.8 percentage points for C_2 was caused by the damage of the edge seal, which was necessary for refilling the module.

Although collector C_2 was not gas-tight during the test, the measurements still allow for an interpretation of the effect of argon concentration on the efficiency. A linear concentration drop during testing was assumed, yielding an average value of $\bar{c}_{ar} = 90.3$ %. This arithmetic mean value was used for further evaluations of the performance tests.

3.3 Measurement of collector efficiency and thermal losses

The efficiency curves (solid lines) and operating points (circles) measured during the test are shown in Figure 6. The collector efficiency η is plotted for five different temperature levels $T_{red} = (T_m - T_a) \,/\, G$. Each operating point was measured four times. The error bars indicate the expanded measurement uncertainty. The method to calculate the error was taken from Mathioulakis et al. [22]. In that process, both uncertainties associated with the calibration of the sensors and uncertainties resulting from the experimental data were considered. For one measurand both types were merged by computing the so-called combined uncertainty as the root mean square of the two uncertainties. As a final step, the sensor data uncertainties were propagated so that Eq. 1 could be applied. For this purpose, Eq. 17 was used, where $w = f(x, y, z, \ldots)$.

$$\Delta w = \sqrt{(\frac{\partial f}{\partial x})^2 \Delta x^2 + (\frac{\partial f}{\partial y})^2 \Delta y^2 + (\frac{\partial f}{\partial z})^2 \Delta z^2 + \cdots} \qquad \text{Eq. (17)}$$

Measurement error in Figure 6 is given as the expanded uncertainty with a confidence level of 95 %. Solid lines are quadratic interpolations and extrapolations of the measured data. For the third operating point, a temporary fluctuation of the solar irradiance was observed, which caused a larger deviation within the four measurements for that collector temperature level. Therefore, the uncertainty is larger as compared to the other measured values. Dashed lines in the diagram represent efficiency curves from other collectors/authors, which have been added for reference.

For lower temperature levels in the range $0 \leq T_{red} \leq 0.02$ m^{2}K/W the difference between the efficiency curves is smaller as compared to higher values of T_{red}. With increasing T_{red}, the curves diverge from another. Consequently, the argon concentration affects the thermal efficiency mainly at higher operating temperatures. Since the convective losses of flat-plate collectors become more dominant at higher temperatures, the effect of argon concentration on the convective losses was confirmed by the measurements.

The prototypes in this study show a higher temperature sensitivity as compared to the IGFPCs investigated by Giovannetti et al. [21] and Riess et al. [10]. The examined prototype with $c_{ar} = 0$ % performs worse for $T_{red} > 0.045$ m^{2}K/W and better at lower temperatures. When $c_{ar} = 50$ %, the intersecting point shifts towards $T_{red} = 0.08$ m^{2}K/W and when $c_{ar} = 90$ %, it shifts towards $T_{red} = 0.09$ m^{2}K/W. To further compare these results with the findings of the literature, the increase in efficiency from $c_{ar} = 0$ % to $c_{ar} = 90$ % was computed for $T_{red} = 0.05$ m^{2}K/W. The difference was found to be 5.1 percentage points, which is slightly out of the range (2.6 to 4.6 percentage points) that resulted from analysing existing studies (cf. Section 1.2). A potential explanation for this is given in Section 4. The results show that higher argon concentrations lead to a significant increase in thermal efficiency at higher temperatures.

As described in Section 1.2, by analysing the investigations of Vestlund et al. [8] and Riess et al. [10], the increase in efficiency can be quantified as 2.6 to 4.6 percentage points when using argon fillings instead of air. A possible explanation for the deviation from this study is that the IGFPC design of the previous studies was different. There, only the front side of the absorber was in contact with argon. The IGFPCs in this study, however, contain absorbers that are fully surrounded by argon. Therefore, the effect of the argon concentration was expected to be higher than that stated in the literature.

This is also evident when comparing the collector efficiency parameters $a_1$and a_2. On the one hand, the quadratic heat loss coefficient a_2 does not appear to be affected systematically by the argon concentration (for increasing c_{ar}: $0.01554;\ 0.0106;\ 0.01361$). On the other hand, a collector with a higher argon concentration appears to have smaller values for a_1 confirming that the convective heat losses affected by the argon concentration (4.75; 4.402; 3.909).

For a further analysis on how argon affects the power balance of IGFPCs, the thermal losses were disaggregated into optical losses $\dot{Q}_{opt}$, convective losses $\dot{Q}_{conv}$ and remaining losses $\dot{Q}_{rem}$. $\dot{Q}_{opt}$ was computed from the optical efficiency (η_0) values and the solar irradiance measurements. $\dot{Q}_{conv}$ was determined by applying Eq. 15 and $\dot{Q}_{rem}$ was computed as the residual power within the energetic balance of the system.

In Figure 7, the energy flux distribution is shown in a pie chart representation. The values were computed as arithmetic mean values from all operating points (cf. Table A.2). On average, 16 % of the solar energy will be dissipated during energy conversion as a result of reflection and absorption at the front cover and surrounding components. The average convective losses of the IGFPC prototypes were computed from the correlations of Summ et al. [13] and are 11 %, 9 %, and 8 %, respectively. With an increasing argon concentration, the losses were reduced as outlined above. The remaining losses make approximately a tenth of the total solar irradiance. This division of energy underlines that higher concentrations of argon lead to higher thermal efficiencies of IGFPCs by reducing their convective losses. These results suggest furthermore, that radiative losses appear not to be affected significantly by argon fillings.

To describe the effect of argon concentration on the thermal efficiency of IGFPCs, the typical operating range $0.05 \leq T_{red} \leq 0.08$ m^{2}K/W was further analysed. Figure 8 shows the average thermal efficiency $\bar{\eta}$ of the examined prototypes versus the argon concentration c_{ar} for three concentration levels. Data was taken from Figure 6 by computing the arithmetic mean values for $\bar{\eta}$ within the specified temperature range. A quadratic polynomial was added as a trend line (dashed line). Error bars indicate the uncertainty of the measurement. Resulting from that, a coloured area highlights the range in which the trendline can deviate.

The difference between $c_{ar} = 0$ % and $c_{ar} = 90$ % can be quantified by an average increase of $\bar{\eta}$ by 6.7 ± 4.8 percentage points. From $c_{ar} = 0$ % to $c_{ar} = 50$ % the average efficiency increase was determined as 5.1 ± 4.5 percentage points. In the range from $c_{ar} = 50$ % to $c_{ar} = 90$ % the measured effect is smaller and was determined to be 1.7 ± 4.8 percentage points. It has to be noted that the argon concentration was not constant during the performance test after refilling the collector. Hence, it is possible that $\partial\bar{\eta} \,/\, \partial c_{ar}$ was slightly underestimated in this study for $c_{ar} > 50$ %. However, even if the concentration during the second performance test was not 90 % but 82 %, this would not affect the conclusions of this study. The reason for this is that the effect of c_{ar} on $\bar{\eta}$ would still be significantly smaller for $50 < c_{ar} \leq 82$ % as compared to the range $0 \leq c_{ar} \leq 50$ %.

4 Conclusions

The objective of this research was to determine the effect of the argon concentration c_{ar} on the efficiency of insulating glass flat-plate collectors. For this purpose, theoretical calculations based on the properties of the gas mixture were carried out and prototypes were experimentally studied using an outdoor solar thermal collector test rig.

This study showed by theoretical and experimental investigations that the effect of c_{ar} on $\bar{\eta}$ is very likely to be non-linear. This confirms the theoretical computations from Section 3.1. The insulating glass collector has its peak performance when argon concentration is at its maximum. The conducted measurements indicate that $\partial^2\bar{\eta} \,/\, \partial {c_{ar}}^2 < 0$ which implies that a change in c_{ar} between 0 % and 50 % has a larger effect on the thermal efficiency than a change between 0 % and 100 %. An increase in argon concentration from 0 % to 50 % has almost twice the effect on average thermal efficiency as an increase from 50 % to 90 %.

Consequently, argon losses in the range from $50 \leq c_{ar} \leq 100$ % are less critical as compared to argon losses at $c_{ar} < 50$ %. On the one hand, this confirms the findings of Giovannetti and Kirchner [21] who observed that small argon leakages of about 1 percentage point led to identical collector heat loss coefficients. On the other hand, it was expected that $\partial^2\bar{\eta} \,/\, \partial {c_{ar}}^2 \approx 0$. In this study, an argon leakage from 90 % to 50 % has led to a mean reduction of the collector performance by 1.7 ± 4.8 percentage points and is therefore less critical than assumed. In conclusion, for the long-term durability of insulating glass flat-plate collectors, it is most important to ensure that $c_{ar} > 50$ %.

Finally, under the assumption that the non-linearity will be confirmed by further measurements, we conclude that argon leakages up to 50 percentage points are acceptable for this collector type. As a result, collector designers should ensure that the argon concentration does not halve within the lifetime of the collector. Typically, the lifetime of many FPCs are 20 years. This implies that the acceptable leak rate for insulating glass flat-plate collectors is 2.5 percentage points per year. These long-term investigations have not been carried out yet and should be considered for future research in this field.

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Appendix

[Remark: The Appendix contains tables A.1 and A.2.]

References

[1] Tschopp D, Tian Z, Berberich M, Fan J, Perers B, Furbo S. Large-scale solar thermal systems in leading countries: A review and comparative study of Denmark, China, Germany and Austria. Applied Energy 2020;270:114997. doi:10.1016/j.apenergy.2020.114997.

[2] Perez-Mora N, Bava F, Andersen M, Bales C, Lennermo G, Nielsen C et al. Solar district heating and cooling: A review. Int J Energy Res 2018;42(4):1419–41. doi:10.1002/er.3888.

[3] Weiss W, Spörk-Dür M. Solar Heat Worldwide: Global Market Development and Trends in 2020 Detailed Market Data 2019. [July 03, 2021]; Available from: https://www.iea-shc.org/Data/Sites/1/publications/Solar-Heat-Worldwide-2021.pdf.

[4] Riess H, Brandmayr S, Zörner W. A Novel Production Technique for Flat Plate Solar Collectors with a Fully Adhesive Edge Bond. In: Frank E, Papillion P, editors. Conference proceedings / EuroSun 2014, International Conference on Solar Energy and Buildings, Aix-les-Bains, France, 16 - 19 September: Proceedings of the EuroSun 2014 Conference. Freiburg, Germany: International Solar Energy Society; 2015, p. 1–9. doi:10.18086/eurosun.2014.16.19.

[5] Riess H. Simulation, testing and design of a fully adhesive bonded flat plate solar collector for highly automated production. Ph.D. Thesis. Leicester. Available from: https://dora.dmu.ac.uk/bitstream/handle/2086/15041/e-thesis%20submission%20Hermann%20Riess.pdf ; 2017.

[6] VDI e.V. VDI-Wärmeatlas: Mit 320 Tabellen. 11th ed. Berlin: Springer Vieweg; 2013.

[7] Menzies GF, Wherrett JR. Multiglazed windows: potential for savings in energy, emissions and cost. Building Services Engineering Research and Technology 2005;26(3):249–58. doi:10.1191/0143624405bt132tn.

[8] Vestlund J, Rönnelid M, Dalenbäck J-O. Thermal performance of gas-filled flat plate solar collectors. Solar Energy 2009;83(6):896–904. doi:10.1016/j.solener.2008.12.005.

[9] Vestlund J. Gas-filled, flat plate solar collectors. Ph.D. Thesis. Gothenburg. Available from: https://www.diva-portal.org/smash/record.jsf?pid=diva2%3A523432&dswid=-5121; 2012.

[10] Riess H, Klärner M, Zörner W, Greenough R. Thermal Simulation and Efficiency of a Hermetically Sealed Flat Plate Collector with a Fully Adhesive Edge Bond. In: Martínez V, González J, editors. Proceedings of EuroSun2016. Freiburg, Germany: International Solar Energy Society; 2016, p. 1100–1113. doi:10.18086/eurosun.2016.07.07.

[11] Summ T, Ehrenwirth M, Trinkl C, Zörner W. Entwicklung eines Großflächenkollektors in Isolierglasbauweise für den Einsatz in Wärmenetzen. In: Conexio GmbH, editor. Online-Symposium Solarthermie und innovative Wärmesysteme. Tagungsunterlagen; 2020, p. 435–448.

[12] Summ T, Scherer C, Ehrenwirth M, Trinkl C, Zörner W. Messtechnische Untersuchung von Kleinmustern eines Isolierglaskollektors anhand von Temperaturbelastungstests. In: Conexio GmbH, editor. Tagungsunterlagen: Online-Symposium Solarthermie und innovative Wärmesysteme. Tagungsunterlagen, 1st ed. Pforzheim: Conexio GmbH; 2021, p. 401–408.

[13] Summ T, Abdalsalam M, Ehrenwirth M, Trinkl C, Zörner W. A Detailed Investigation on the Convective Heat Transfer Inside the Enclosed Cavity of Insulated Glass Solar Thermal Flat-Plate Collectors. In: International Solar Energy Society, editor. Proceedings of the Solar World Congress 2021; 2021. doi:10.18086/swc.2021.22.09.

[14] Giovannetti F, Kirchner M, Kliem F, Hoeltje T. Development of an Insulated Glass Solar Thermal Collector. Energy Procedia 2014;48:58–66. doi:10.1016/j.egypro.2014.02.008.

[15] Poling BE, Prausnitz JM, O'Connell JP. The properties of gases and liquids. 5th ed. New York, NY: McGraw-Hill; 2001.

[16] Neufeld PD, Janzen AR, Aziz RA. Empirical Equations to Calculate 16 of the Transport Collision Integrals Ω (l, s)* for the Lennard- Jones (12–6) Potential. The Journal of Chemical Physics 1972;57(3):1100–2. doi:10.1063/1.1678363.

[17] Wassiljewa A. Wärmeleitung in Gasgemischen. Mitteilung aus dem Institut für physikalische Chemie der Universität Göttingen. Physikalische Zeitschrift 1904;5:737 - 732.

[18] Mason EA, Saxena SC. Approximate Formula for the Thermal Conductivity of Gas Mixtures. Phys. Fluids 1958;1(5):361. doi:10.1063/1.1724352.

[19] Wilke CR. A Viscosity Equation for Gas Mixtures. The Journal of Chemical Physics 1950;18(4):517–9. doi:10.1063/1.1747673.

[20] Asphaug SK, Jelle BP, Gullbrekken L, Uvsløkk S. Accelerated ageing and durability of double-glazed sealed insulating window panes and impact on heating demand in buildings. Energy and Buildings 2016;116:395–402. doi:10.1016/j.enbuild.2016.01.015.

[21] Giovannetti F, Kirchner M. Performance and Reliability of Insulated Glass Collector Prototypes. In: Frank E, Papillion P, editors. Conference proceedings / EuroSun 2014, International Conference on Solar Energy and Buildings, Aix-les-Bains, France, 16 - 19 September: Proceedings of the EuroSun 2014 Conference. Freiburg, Germany: International Solar Energy Society; 2015, p. 355–361. doi:10.18086/eurosun.2014.16.07.

[22] Mathioulakis E, Voropoulos K, Belessiotis V. Assessment of uncertainty in solar collector modeling and testing. Solar Energy 1999;66(5):337–47. doi:10.1016/S0038-092X(99)00034-1.

Figure captions and tables

Figure 1: The effect of argon concentration on thermal efficiency was investigated both theoretically and experimentally. Convective losses were studied theoretically, whereas experimental work was carried out to measure the thermal efficiency of prototype collectors.

Figure 2: The simplified schematic structure of an IGFPC shows that the absorber is fully surrounded by argon. In contrast to conventional collectors, a glass pane encloses the collector at its back. Fluid channels are not drawn for reasons of simplicity.

Figure 3: Test setup of the performance measurements on the THI solar tracker. Two prototypes were tested simultaneously and the collector characteristics were measured according to the ISO 9806 standard.

Figure 4: Hydraulic test setup for the thermal performance tests according to the ISO 9806 standard. Only one collector is shown in this schematic drawing.

Figure 5: Thermal conductivity λ_{mix} and convective heat transfer coefficient $\bar{h}$ show a slight non-linearity with respect to the concentration of the argon-air mixture c_{ar}. Gas temperature was 25°C and pressure 101325 Pa. The correlation from Summ et al. [13] was used to obtain $\bar{h}$, with $\varphi = 35°$, $d = 15$ mm, $\Delta T = 50$ K.

Figure 6: Efficiency (η) curves of both collector prototypes (C1, C2, solid lines) indicate that the effect of argon concentration c_{ar} is non-linear. The tested prototypes show efficiencies higher than those of the modules from other investigations in the literature. The efficiency coefficients are:

— $\eta_0 = 0.8371$, $a_1 = 4.75$, $a_2 = 0.01554$; — $\eta_0 = 0.8435$, $a_1 = 4.402$, $a_2 = 0.0106$; — $\eta_0 = 0.8408$, $a_1 = 3.909$, $a_2 = 0.01361$

Figure 7: The energy flux distribution shows that argon concentration c_{ar} mainly affects the convective losses of IGFPCs.

Figure 8: An increase in argon concentration c_{ar} from 0 % to 50 % has almost twice the effect on average thermal efficiency $\bar{\eta}$ as an increase from 50 % to 90 %. Measurements were evaluated for $0.05 \leq T_{red} \leq 0.08$ m^{2}K W^{-1}. $\alpha = -6.663 \times 10^{-6}$, $\beta = 0.001348$ and $\gamma = 0.457$.

Table 1: The gas properties of air and argon that were used to compute viscosity, density, heat capacity, and thermal conductivity according to the ideal gas law and kinetic gas theory.

Gas	Molar Mass M	Collision parameter σ	Energy parameter ε/k_B	Degrees of freedom f
Air	$28.959\,\frac{\text{kg}}{\text{kmol}}$	3.711 Å $= 0.3771$ nm	78,6 K	5
Argon	$39.948\,\frac{\text{kg}}{\text{kmol}}$	3.542 Å $= 0.3542$ nm	93,3 K	3

Table 2: Invasive measurement of argon concentration shows that argon does not leak after production or during performance testing. Refilling of the module caused an argon leak and a concentration drop.

Measurement	$c_{ar,1}$ in %	$c_{ar,2}$ in %
Prior to performance test #1	50.3	0.0
After performance test #1	50.3	0.0
After argon refill	-	98.7
After performance test #2	-	81.9
Two days after performance test #2	-	53.0

Table A.1: List of physical constants and collector properties.

Symbol	Value	Unit
A_{coll}	3.881	m^2
A_{abs}	3.658	m^2
R	8.314	J mol^{-1}K^{-1}
k_B	1.380649×10^{-23}	J K^{-1}
d_f	16	mm
d_b	20	mm

Table A.2: The measurement data from performance tests according to ISO 9806. Each operating point was measured four times. Thermal and optical losses were derived from the measured data as described in Sections 2.3, 2.4, and 3.3.

C_2 – 0 %						**C_1 – 50.3 %**						**C_2 – 90.3 %**					
$T_m - T_a$	$\dot{Q}$	$\dot{Q}_{opt}$	$\dot{Q}_{conv}$	$\dot{Q}_{rem}$	η	$T_m - T_a$	$\dot{Q}$	$\dot{Q}_{opt}$	$\dot{Q}_{conv}$	$\dot{Q}_{rem}$	η	$T_m - T_a$	$\dot{Q}$	$\dot{Q}_{opt}$	$\dot{Q}_{conv}$	$\dot{Q}_{rem}$	η
K	W	W	W	W	-	K	W	W	W	W	-	K	W	W	W	W	-
73.9	1493.7	619.1	895.2	792.8	0.393	74.1	1706.0	594.8	788.2	711.7	0.448	77.0	1832.1	625.9	717.4	756.0	0.466
73.6	1507.5	622.2	891.1	798.8	0.395	73.9	1726.5	597.7	784.8	710.5	0.452	76.8	1838.3	626.6	716.1	754.8	0.467
73.6	1526.9	625.4	891.8	795.2	0.398	73.9	1751.2	600.8	785.5	701.7	0.456	76.8	1853.9	629.9	715.6	757.4	0.469
73.5	1542.5	629.1	889.9	800.5	0.399	73.8	1773.5	604.4	783.9	700.2	0.459	76.4	1859.8	629.4	711.2	753.1	0.470
55.4	2100.9	642.5	625.1	575.9	0.533	55.6	2257.4	617.3	550.4	519.4	0.572	57.5	2293.0	631.6	497.9	544.9	0.578
55.5	2110.2	646.3	626.8	584.1	0.532	55.7	2268.1	620.9	552.0	526.5	0.571	57.5	2299.5	632.8	498.0	544.7	0.578
55.2	2117.9	647.8	622.9	588.4	0.533	55.5	2277.7	622.4	548.4	528.5	0.572	57.5	2294.0	632.9	497.7	550.8	0.577
54.9	2132.2	650.3	618.2	591.6	0.534	55.1	2292.3	624.8	544.3	530.9	0.574	56.9	2287.6	630.1	491.7	548.5	0.578
36.5	2720.6	679.7	368.0	404.3	0.652	36.7	2814.6	653.0	324.2	380.9	0.674	38.3	2690.0	632.4	296.8	353.3	0.677
36.7	2583.6	648.0	370.4	375.7	0.650	36.8	2677.2	622.5	326.2	351.8	0.673	38.3	2685.8	632.9	297.4	359.7	0.676
36.4	2752.7	675.1	367.1	349.7	0.664	36.5	2851.7	648.6	323.2	321.1	0.688	37.9	2688.6	632.7	292.7	360.2	0.676
36.4	2755.4	682.2	368.1	382.3	0.658	36.6	2857.2	655.4	324.1	351.4	0.682	38.0	2677.6	630.4	293.7	358.1	0.676
18.4	3006.9	655.9	153.9	210.0	0.747	18.5	3053.3	630.2	135.5	207.8	0.758	19.4	2992.7	624.4	123.3	181.7	0.763
18.7	3001.8	653.3	156.2	199.3	0.748	18.7	3047.4	627.6	137.6	198.0	0.759	19.0	2949.8	614.8	120.1	177.1	0.764
18.3	2991.5	651.5	151.9	204.6	0.748	18.4	3036.9	625.9	133.8	202.9	0.759	19.1	2949.9	617.2	121.3	188.5	0.761
18.8	3002.8	653.4	157.8	197.2	0.749	18.9	3054.2	627.7	139.0	190.3	0.761	18.6	2951.0	616.6	116.9	188.8	0.762
9.3	3109.1	640.9	63.8	120.4	0.790	9.4	3149.0	615.7	56.6	113.0	0.800	9.6	3057.9	606.4	50.1	94.6	0.803
9.5	3096.4	639.1	65.6	122.1	0.789	9.6	3140.5	614.0	58.1	110.6	0.800	9.9	3030.9	603.6	52.2	105.0	0.799
9.6	3092.1	637.9	66.3	119.7	0.790	9.7	3138.5	612.8	58.7	106.0	0.801	9.3	3031.1	603.0	47.8	105.8	0.800
9.9	3083.3	637.7	69.0	124.7	0.788	10.0	3130.1	612.6	61.1	110.8	0.799	9.1	3035.0	603.2	46.7	104.1	0.801