Renewable Energy 230 (2024) 120898

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Reducing convective losses in a solar cavity receiver VoCoRec by creating a controlled vortex of returned air

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A R T I C L E I N F O

Keywords:
Cavity receiver
Solar tower
Return air
Air return ratio
Thermal efficiency
Convective loses
Vortex

A B S T R A C T

The efficiency of air-type solar towers influences the minimal cost of electricity/heat produced by them, which limits their use despite the widespread use of many forms of concentrated sun power plants. Nonetheless, the temperature potential of this kind of concentrated plant is the highest. To improve the efficiency of an air-type solar tower, a technique for reducing convective energy losses with return air is therefore suggested. In order to increase a cavity receiver's thermal efficiency, a little-known concept called vortex creation will be discussed in this work. The article models different ways of creating an air vortex inside the cavity receiver. Using the VoCoRec design as an example, cases are shown where the vortex increases and decreases the thermal efficiency of the receiver. The concept of Air Return Ratio (ARR) is used to determine the convective losses in a solar collector. This coefficient indicates the convective losses of the receiver due to buoyancy forces and has a direct proportional dependence on the convective efficiency coefficients of the receiver. The VoCoRec receiver, which incorporates the directional vortex inside the receiver, increased the air return coefficient by 4 % (at the same air mass flow rate). The dependence of the air return coefficient on different angles of the air outlet to the absorber plane, including in the radial direction, was also investigated. Increasing the angle of inclination of the air outlet to the main absorber increases the air return coefficient in all cases, but also increases the aerodynamic drag of the receiver (pressure drop).

1. Introduction

Solar tower or central receiver systems use sun-tracking mirrors to focus sunlight onto a receiver at the top of the tower, heating a heat transfer medium and generating high-temperature heat. The advantage of this type of solar plant is the high concentration of radiation in the receiver, so that the generated energy is transferred to the coolant at very high temperatures (i.e. 560 °C up to more than 1000 °C). As a heat transfer medium, water/steam, molten salt, solid particles and air are being considered [1,2]. Molten salt is the most widely also commercially used material [3,4], as it has a high heat capacity and good heat transfer capabilities. But in practice the use of salts above 560 °C is critical due to thermal stability [5,6], although now scientific developments are underway to increase this potential [3]. Air is an alternative heat transfer medium that can withstand high temperatures without chemical transformations. The low heat transfer capability of gases is overcome by using so-called volumetric receivers where the concentrated radiation is absorbed in the depth of a porous solid structure and transferred to a gaseous medium flowing through it. Many research and development activities dealt with the development of this so-called open volumetric receiver technology [7]. The open volumetric receiver has been developed since the 1990s as the so-called HiTRec modular receiver design with ceramic absorber modules held in a steel support structure [8]. It is demonstrated with the Solar Tower Jülich as a complete power plant of 1,5 MWe [9].

The characteristic and eponymous nature of open volumetric receivers is that the air that is used as the heat transfer fluid is sucked in from the immediate vicinity of the receiver front that is open to the environment. In contrast to the other receiver technologies (water/steam, molten salt, etc.), the open volumetric receiver does not have a closed circuit for the heat transport medium. In order to utilize the eventually remaining exergy in the heat transfer fluid after the heat consumer (e.g. the steam generator, storage or reactor) the used air is redirected to the receiver and released directly into the open air before the receiver aperture. The heat transfer fluid circuit is still not completely closed but directly exposed to ambient influences, in particular to convective mixing with ambient air. Hence, only part of the redirected air (and its enthalpy) can be reused by being sucked into the

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https://doi.org/10.1016/j.renene.2024.120898
Received 9 October 2023; Received in revised form 14 June 2024; Accepted 27 June 2024

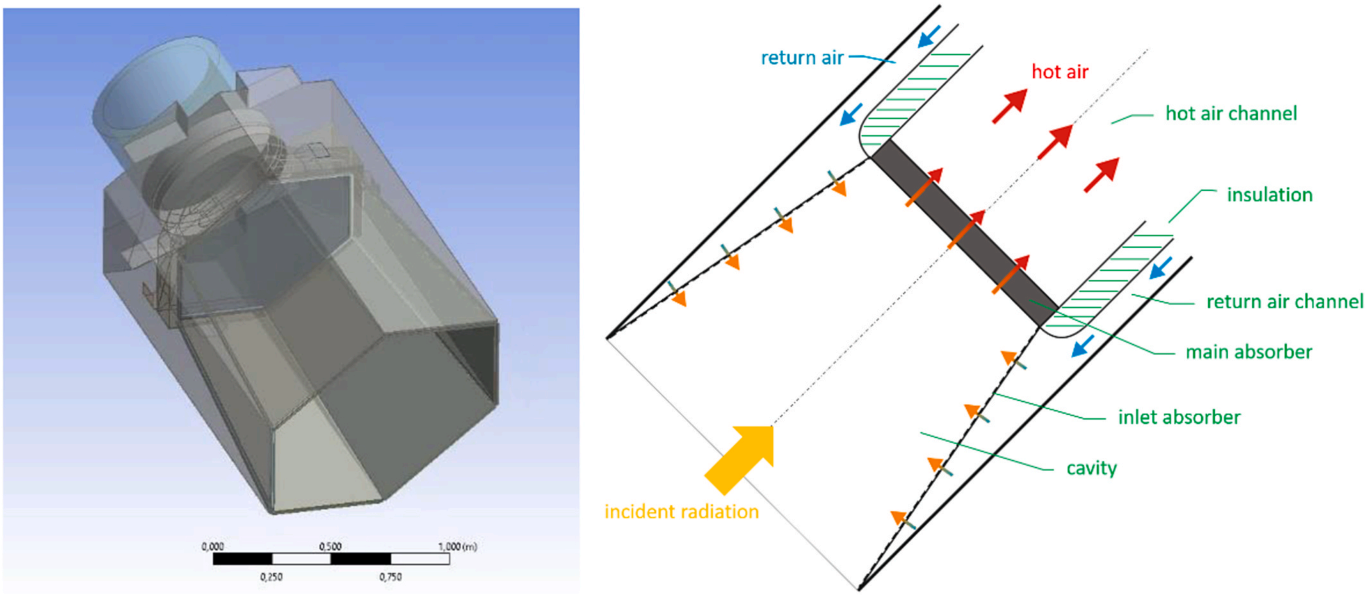

Fig. 1. Geometric model and appearance VoCoRec.

porous receiver structure. The ratio of re-used heat transfer fluid is called the air return ratio ARR. Refer to [10,11] for more details about the HiTRec receiver and the concept of air return in open volumetric receivers.

Return air losses of open volumetric receivers have been investigated in several works [12–14]. The reduction of convective heat losses in tower receivers in general has also been addressed in several previous works: the articles [15,16] describes and analyzes different measures and engineering solutions to reduce energy losses with the outgoing air. The study of the optimal parameters of the air curtain used to locally reduce convective heat loss from the heated surface of the solar tower receiver, considered in [17], confirmed that convective heat loss from the heated surface of the receiver with a length of 1.8 m can be reduced by 31,2 % for Tw = 110 °C by changing the movement of the external flow. Another paper [18] proved that the efficiency of a suction nozzle installed in the lower part of the cavity receiver is up to 80 % due to changes in the flow aerodynamics behind the receiver cavity.

These studies deal with convective heat loses of hot receiver surfaces. In contrast to that, our work deals with convective losses of the heat transfer medium itself.

To overcome the problem of return air loss to the environment structurally a new receiver design has been presented recently, the so-called volumetric conus receiver, “VoCoRec” [19].

The VoCoRec receiver was designed with the objective to reduce radiation and convection losses for the open volumetric receiver principle by adding an active cavity to a central main absorber. This leads to a two-stage air heating and is taken here as the base model for improvements [20]. This type of receiver was designed in a hexagonal modular shape to be deployed for a wide range of power levels. The VoCoRec structure allows for preheating of the air in the so-called outlet (side) absorber and significantly increases the air return ratio (ARR) due to the radial direction of the outgoing air (Fig. 1) to values up to 90 %. The efficiency of this receiver depends on its angle of inclination and lies in the range of 85,5–94,8 % at the optimum mass flow load. Also, the shape of the tower, the shape of the receiver, and the geographical conditions will affect the convective losses from interaction with the outside air.

The purpose of this paper is to study the possibility of further reducing return air losses in a VoCoRec receiver module by forming a return air vortex. ARR (air return ratio) is numerically equal to the ratio of the amount of returned air passing through the main absorber to the total amount of returned air. This coefficient indicates the convective losses of the receiver due to buoyancy forces and has a direct proportional dependence on the convective efficiency coefficients of the receiver.

A detailed thermal and flow analysis was conducted in a previous study to assess the technical potential of this new receiver design. In [20] the ARR of a single module was calculated based on CFD simulations depending on the air mass flow and the tilt angle of the aperture normal with respect to the horizontal. At full load the ARR varied from 85,5 % to almost 95 % at tilt angles ranging from 0° to 60°. The ARR at 50 %-part load was lower, ranging between 70,6 % to almost 92 % for the same tilt angles. This is drastically more in comparison to the usual open volumetric receiver without cavity, showing ARR values between 50 % and 65 % [21]. But, the ARR is decreasing with unit size, as can be seen in [22], where the thermal performance of the VoCoRec design was evaluated with a thermal model. For four different sizes the thermal efficiency was determined to vary between 88,6 % and 81,1 %, with the efficiency decreasing with size due to a decreasing ARR. A cost estimation in the same paper showed a decrease of specific cost with size, as expected, so that a trade-off between cost and efficiency would be needed for engineering.

The aim of this study is therefore to investigate whether the flow inside the cavity of a VoCoRec can be stabilised by a vortex flow in order to maintain a high ARR even at larger unit sizes.

2. Method

The Ansys@ CFX (includes CFD-Post) 2023 R1 was used for computer modeling. Numerical simulations were performed on two geometric models of VoCoRec with different components of the velocity vectors of the returned air outlet from the outlet absorber, see Fig. 1. The inlet air temperature was varied for different cases from 150 °C to 556 °C. The angle of inclination of the receiver’s symmetry axis is 25° to the horizon (gravity along the z-axis, which is inclined 25° to the horizon is -8.89088 m/s^2). Buoyancy reference density 1,1685 kg/m^3 [21]. Porosity option: isotropic, permeability 7.59e-7 m^2, resistance loss coefficient 6.47 m^{-1}. Physics preference is CFD. Solver preference is CFX.

The results were shown to be grid-independent. Due to the acceptable calculation time of about 4 h, the further results are calculated with the grid 3.

The following figures show the surface mesh on the receiver and the

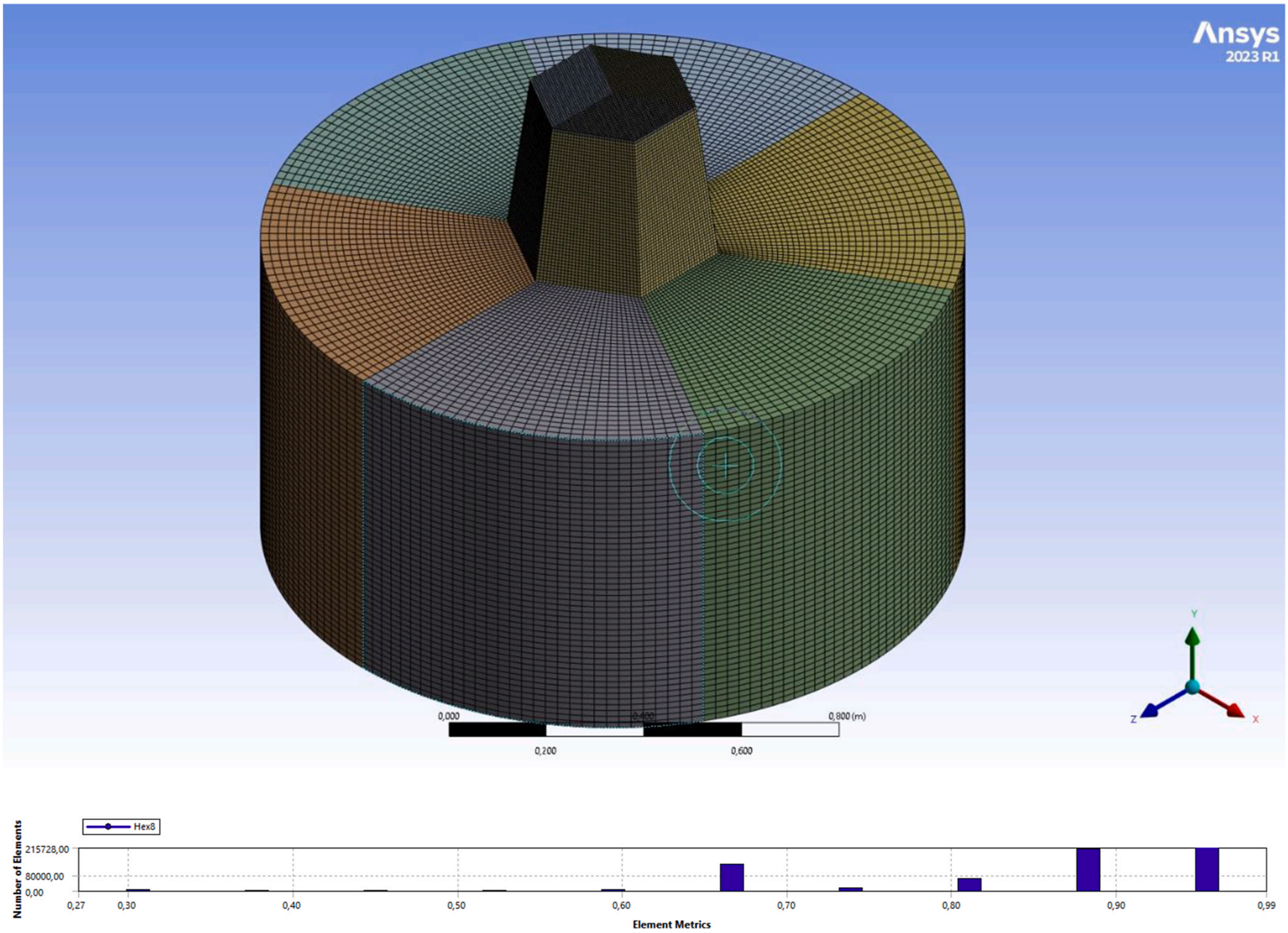

Fig. 2. Calculation mesh of VoCoRec small and element metric quality.

Table 1
Results of greed independence study.

Grid	1	2	3	4
Total number of elements	11 616	80 100	632 700	2 144 475
Max. air temperature, K	803,2	803,1	803,1	803,4
Air return ratio	84,2 %	85,0 %	85,2 %	85,1 %

Table 2
Geometric dimensions of the VoCoRec receiver [20].

	Small	Large
Main absorber width, [mm]	300	1270
Main absorber edge length, [mm]	173	733
Aperture width, [mm]	388	1628
Aperture edge length, [mm]	224	940
Aperture area, [m^2]	0,131	2296
Length [mm]	380	1516
Aperture angle [grad]	6,9	6,9
Scaling factor of all edge lengths in relation to the standards model by [20]	0,361	1516
The recommended mass flow rate [kg/s]	0,21	92,7
Nominal air return rate without vortex [%]	92,7	83,0

tower wall. The mesh is a pure hexahedron mesh, the receiver interior is constructed in the form of an O-grid. The computational mesh consisted of 654 673 nodes (Hex8 elements 632 700) and is shown in Fig. 2.

The turbulence model is the k-omega SST (Shear Stress Transport) turbulence model [23]. It is a hybrid model that combines aspects of both the k-epsilon and k-omega models (see Table 1).

In order to determine the dependence of the air return ratio on the main aerodynamic parameters of the vortex, different components of the outlet air velocity were considered in the structure of the VoCoRec receiver. The geometric dimensions of the VoCoRec receiver considered are given in Table 2.

The usage of a RANS model for the investigation of air return ratio is justified by the findings of Stadler et al. [22] who modelled the Jülich open volumetric receiver with the RANS approach and successfully compared his CFD results to experimental measurements of the air return ratio. Also, Drexelius et al. [12] showed recently that RANS is capable to determine the air return ratio although it is not suitable to resolve fluctuating air flow in detail.

We limit our studies to windless conditions for the scope of this paper being fully aware that this is only the first step of a full analysis. But as Drexelius et al. [12] showed, a RANS model is suitable to calculate time-averaged air return ratio values for both windless and wind affected operation. So, this model can serve for investigation of windy situations in future.

3. Theory and hypothesis

Return air losses are significantly affected by convective currents caused by the difference in density of the returned air and the ambient air [25]. An example of modeling return air loss to the ambient from the VoCoRec receiver is shown in Fig. 3.

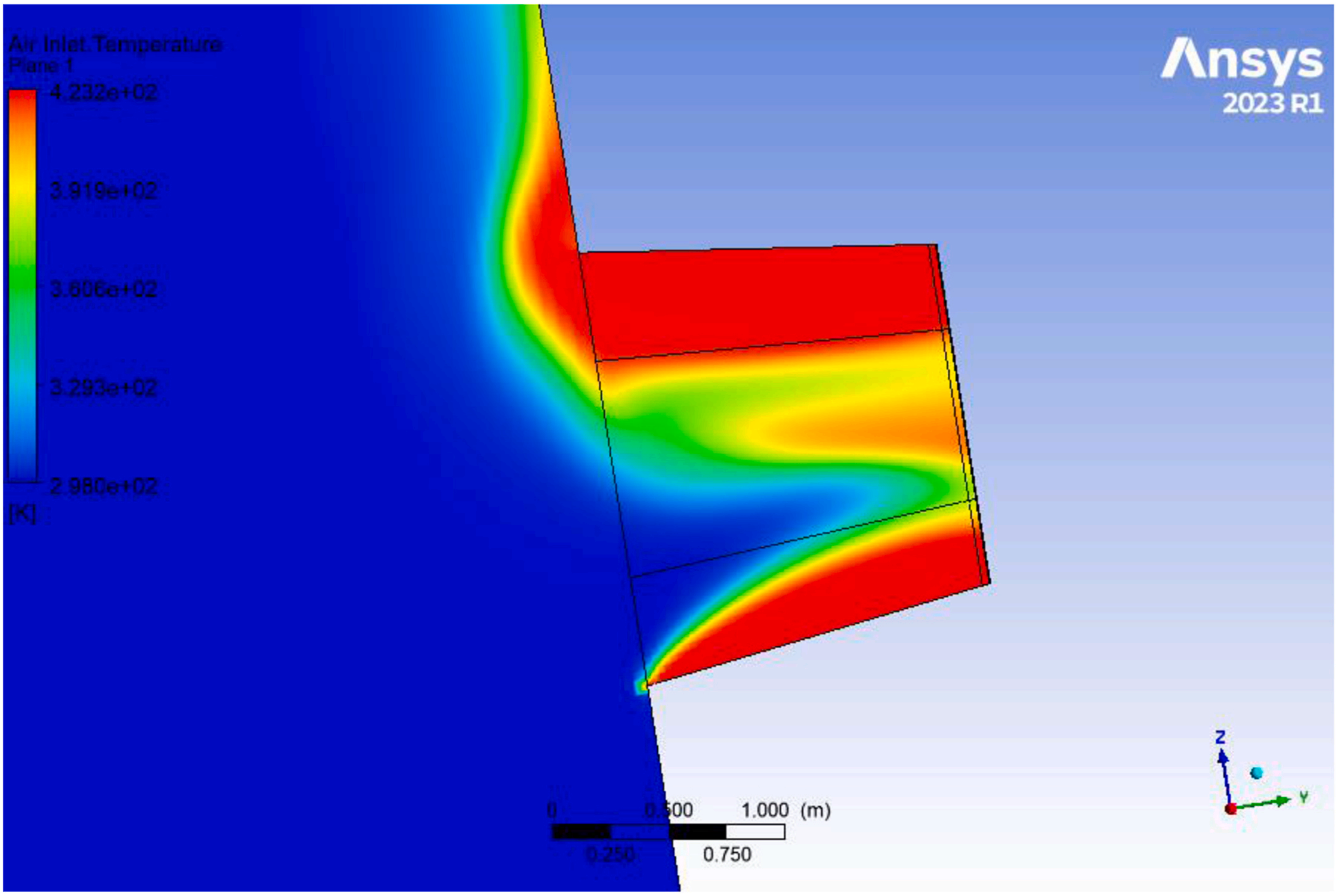

Fig. 3. Simulation of air movement in the VoCoRec receiver M = 5.04 [kg/s] ARR = 0.87. Temperature distribution.

To understand the cause of air leakage, it is necessary to consider its aerodynamics. The relationship between the velocity field and the pressure field is described by the Navier-Stokes equations

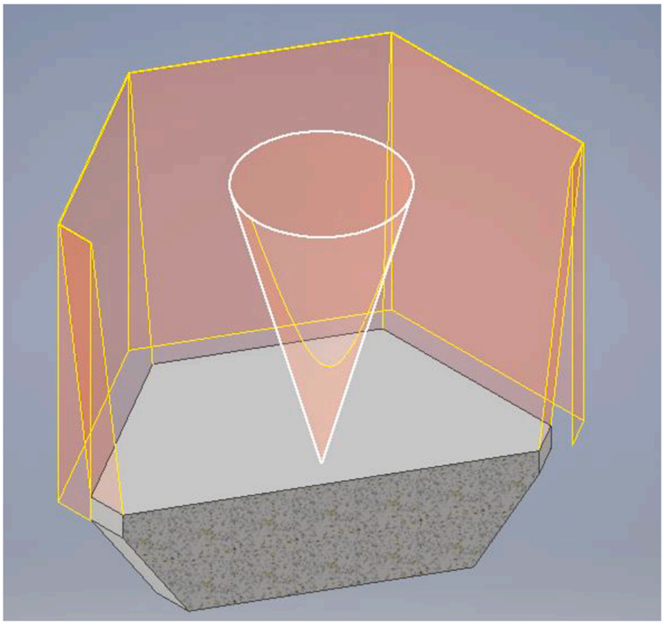

Fig. 4. The concept of an artificial vortex near the surface of the receiver to increase the air return coefficient.

$$\nabla\left(-p+\mu\left(\nabla w+\left(\nabla w^{T}\right)\right)\right)=\rho(w\nabla)w$$

where w – speed;

ρ – density;

p – pressure;

μ - dynamic viscosity.

The loss of already heated air is the energy efficiency indicator for convective losses in each of the above balances. Energy lost to the environment due to the physical heat of the air leaving the solar tower, kW

$$Q_{loss}^{air}=\left(H_{loss}^{air}-H_{amb}^{air}\right)\bullet(1-ARR)\bullet\varepsilon,$$

where H_{loss}^{air} – enthalpy carried with air, kJ/s;

H_{amb}^{air} – enthalpy brought in with ambient air, kJ/s;

ARR – air return ratio;

ε – a delay factor related to the time required to heat the exhaust air to a given temperature, for the stationary case = 1;

The percentage of inlet air that is diverted back into the main absorber is represented by the ARR

$$ARR=\frac{\dot{m}_{\mathrm{ReturnedInletAir}}}{\dot{m}_{Full}}$$

The ARR serves as a pivotal metric in evaluating the performance and efficiency of solar energy systems, particularly focusing on the convective aspects outside the solar receiver. A higher ARR signifies less convective heat losses, resulting in increased energy capture and utilization within the system.

Thus, the ARR is a dimensionless measure of the amount of heated air

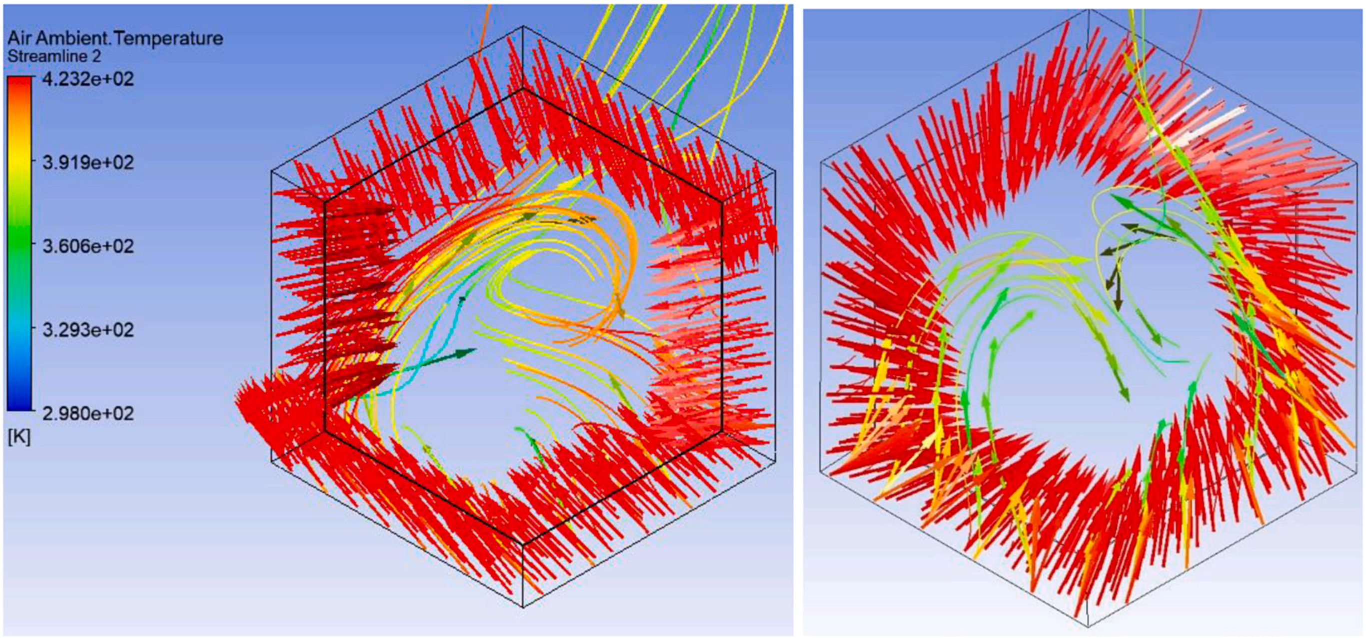

Fig. 5. Twisting of the flow along each geometric plane (left) and cylindrical coordinates with a uniform change in the direction of the guides (rights).

returned to the energy system and a quantitative indicator of the convective component of the solar receiver's energy efficiency.

In the post processor of Ansys@ CFX (includes CFD-Post) 2023 R1 ARR was calculated with the following expression

ARR=Inlet Air.massFlow(.)@Outlet/massFlow(.)@Outlet.

It was found that altering the exit air is necessary to produce a controlled vortex after studying the aerodynamics of the air in front of different receiver types [25]. The primary goal of this paper is to ascertain the optimal angular velocities of the returned air from VoCoRec and how they affect the ARR.

Theoretically, it is possible to increase the ARR by redirecting the air into the suction area of the receiver or by reducing its axial velocity. Reducing the axial velocity of the outgoing airflow can be achieved by increasing the radial flow velocity or by increasing the air pressure. Since increasing the air pressure upstream of the receiver increases the fan work, it is more efficient to dampen the axial velocity. In this case, the absorber must have large enough pores near the outlet to act as a nozzle so as not to dissipate all the energy of the flow. To cool the outlet, end of the absorber, the airflow must be swirled by an internal vane. It is also possible to create an additional vortex around the perimeter of the entire absorber, which acts as an air curtain. The idea of creating a vortex and a vortex near the surface of the absorber is shown in Fig. 4.

As the flow rotates, centrifugal forces are created which deflect the flow away from its axial direction, creating a rarefaction zone which is the vortex flow zone or quasi-solid rotation zone. The outer region is considered to be the potential flow zone.

Finding the zone of inverse currents is given in [24] where the vortex radius is proposed to be found from the "radius of twist of the flux" which is defined as

$$\alpha = arcsin\sqrt[3]{\frac{\sum A_{in}}{\pi \cdot R_n \cdot R_c}\cdot\frac{1}{4\xi}}$$

where ξ - the ratio of the initial momentum loss;

R_c- the aerodynamic cavity resistance;

R_n – the aerodynamic outlet channel resistance;

$\sum A_{in}$ – is the total cross-sectional area of the incoming flow.

Air Output momentum

$$M_{out=}\int_{0}^{2\pi}\int_{R_V}^{R_{Out}}\rho_{out}W_{out}^2 sin\,\alpha_1 cos\,\alpha_1 r^2 drd\varphi$$

The size of the inverse current zone is proposed to be defined as

$$\frac{R_B}{R_C} = 1 - \frac{\sum A_{in}}{\pi \cdot R_\kappa \cdot R_C}\cdot\frac{1}{2tg\alpha}\cdot\frac{1}{\xi}\cdot\frac{\rho_0}{\rho_1}.$$

The resistance of the swirl unit is characterized by the resistance coefficient

$$\xi = \frac{2\Delta P}{\rho w^2}$$

where w – is the average flow rate;

ρ – the flux density at the same location;

ΔP - is the difference between the pressure at the inlet and outlet of the swirl unit.

$$\xi(ARR = 1) \rightarrow min.$$

The boundary between the potential and vortex flow zones represents the surface where the axial component of the absolute velocity vector is zero, i.e. the zero flow surface. This surface is located at a distance from the axis of rotation, called the size of the return flow zone. Working hypothesis 1: There are such angles of swirl of the exhaust air flow around the perimeter of the absorber that an ARR close to 1 and a significant reduction in the aerodynamic drag of the solar circuit can be obtained if the size of the backflow zone near the surface of the main absorber is zero.

For the HitRec technology [22], a structurally vortex flow can be achieved by tangential air supply or by installing guide vanes. For VoCoRec, it is sufficient to adjust the flow direction by means of an outlet from the side absorber.

The calculation of the aerodynamics of the vortex flow is somewhat complicated by the need to take into account the influence of temperature gradients in the different air streams, which leads to the creation of additional convective flows. It is also necessary to consider the conditions of the outside air at the inlet and outlet of the receiving area. This greatly complicates the analytical research process. Since there is no mathematical model of the vortex flow in front of the absorber, it is

Table 3
An example of the distribution of vortex flow velocity components along the planes of the outlet absorber.

Nº outlet absorber	1	2	3	4	5	6
Unit Vector X Component	0,97	−0,34	−0,34	−0,97	0,64	0,66
Unit Vector Y Component	0,17	0,17	0,17	0,17	0,17	0,17
Unit Vector Z Component	−0,175	−0,93	−0,93	0,175	0,75	0,64

proposed to use the numerical method to solve the problem. As a first approximation, select the geometric dimensions of the receiver according to the rational ARR. Carry out computer simulations on the selected geometric models and study the variation of the ARR as a function of the vortex structure [26].

4. Results and discussion

The direction of the velocity vector perpendicular to the outlet plane was chosen as the basic option. The creation of the vortex was considered in two ways: the slope of the air outlet velocity from the outlet absorber along each geometric plane (Fig. 5 - left), and the centred displaced flow given by the cylindrical coordinates of the air outlet velocity through the second absorber (Fig. 5 - right).

The velocity distribution along each geometric plane implies that the surface of a plane of the outlet absorber has the same structure. The porous structure may vary from plane to plane to guide the air along the required paths, but it is not variable along a plane. An example of such a distribution is shown in Table 3.

In the case of the distribution of the vortex flow velocity components along the planes of the outlet absorber, the airflow on the receiver fins

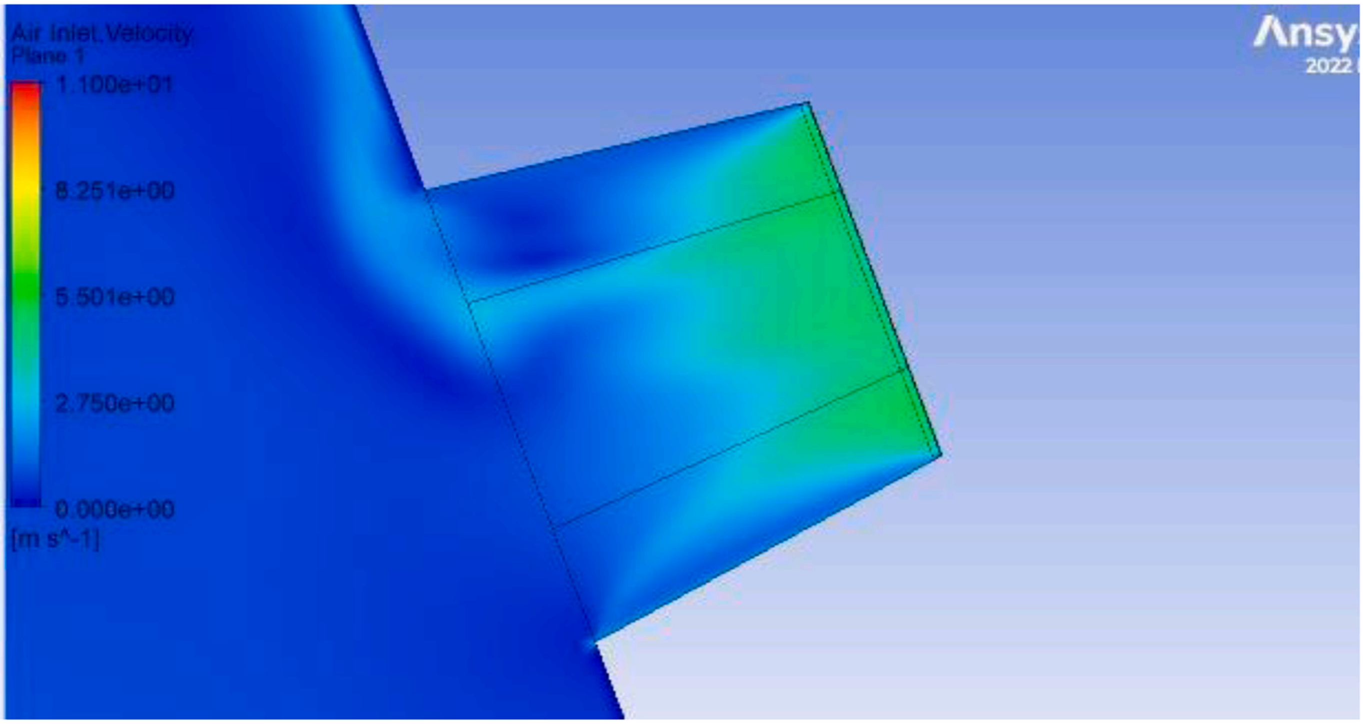

Fig. 6. Speed distribution in VoCoRec Large type receiver with mass Flow 5.04 [kg/s], ARR = 0.87.

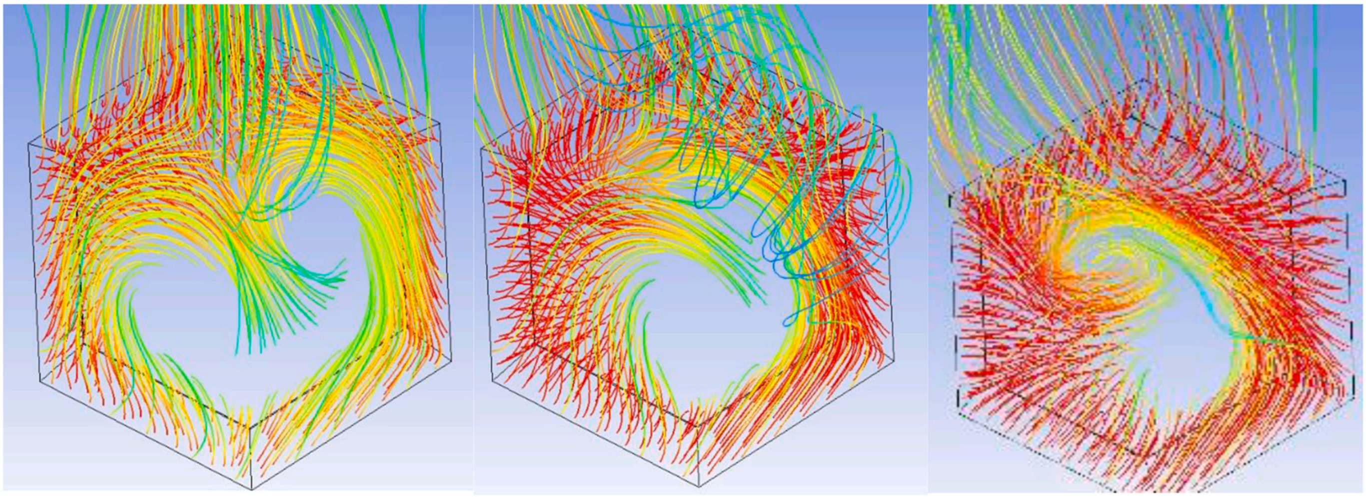

Fig. 7. Comparison of return air current lines for VoCoRec Large $M_1 = 1.2$ kg/s, $M_2 = 2.43$ kg/s, $M_3 = 5.04$ kg/s.

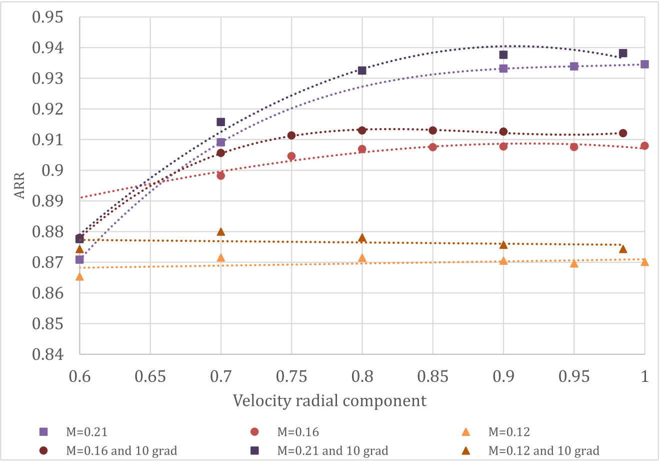

Fig. 8. Variation of ARR for VoCoRec small size for different mass flow M [kg/s] from the radial velocity component (there 1 - no vortex).

has a strong deviation from the desired vortex structure. The multidirectional velocity vectors create additional drag and flow pulsations. The temperature distribution along the vortex flow lines was investigated for each of the six receiver edges. Mass flow through a single surface 0.405 kg/s. The air return ratio for the case considered is ARR = 0.778 compared to ARR = 0.785 without vortex. This example shows that an unsuccessful vortex flow will not have the desired effect and may actually worsen the air return rate.

In addition to increasing the ARR, the creation of a controlled vortex also aims to increase the uniformity of air distribution over the main absorber, ensuring temperature uniformity and preventing local overheating. As the ARR is dependent on the mass flow rate (comparing the temperature distribution for the three mass flow rates of the VoCoRec Large design), it can be concluded that as the mass flow rate increases, the effect of the flow twist on the structure becomes weaker. The higher the mass flow rate, the more uniform the temperature distribution over the internal volume of the receiver. In all cases, the vortex reduces the hot spot on the main receiver.

The cold ambient air is drawn into the return zone. Due to the difference in air density between the air leaving the outlet absorber and the

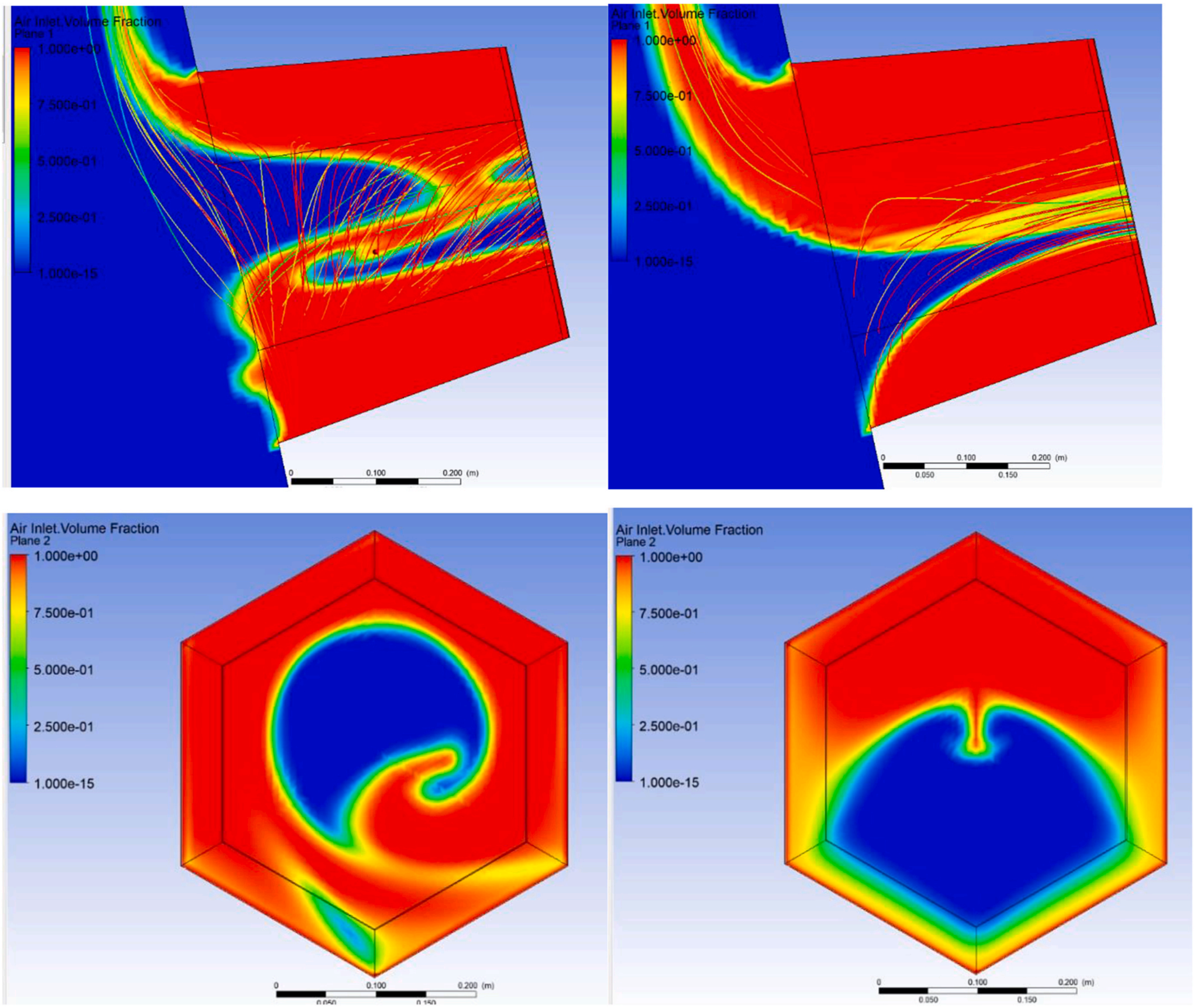

Fig. 9. Air inlet volume fraction in VoCoRec small size with m = 0.21 kg/s, velocity radial component = 0.6, ARR = 0.87 (left) and m = 0.21 kg/s, velocity radial component = 1 ARR = 0.935 (right).

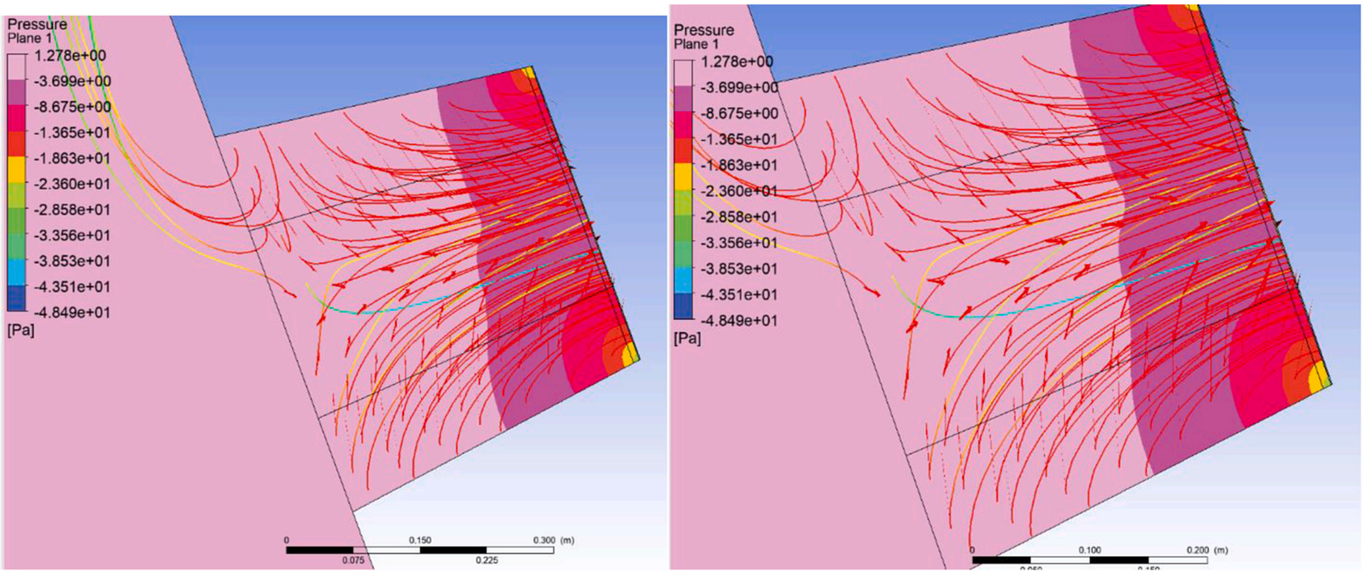

Fig. 10. Air pressure in VoCoRec small size with m = 0.21 kg/s, velocity axial component = -0.174, velocity radial component = 0.7, ARR = 0.92 (left); m = 0.21 kg/s, velocity axial component = -0.174, velocity radial component = 0.985, ARR = 0.94 (right).

ambient air, the vortex centre is shifted to the lower edge of the receiver. The angle of tilt of the receiver to the horizon also causes the vortex centre to shift and a backflow zone to form. The total air velocity in the receiver has a homogeneous distribution up to a certain limit from the main absorber (Fig. 6). Fig. 6 shows the discrepancy between the depth of the receiver and the calculated mass velocity.

Fig. 7 shows the change in flow structure as the mass flow rate, and hence the overall velocity, increases. A possible solution to the problem of vortex irregularity is to optimise the velocity separately for each plane of the outlet absorber to produce a stable flow. The velocity can be found using a design of experiment method for a specific design. However, simpler engineering solutions, such as the effect of spin angle and axial flow direction, are counterintuitively more justified. The red color indicates more heated air.

The results of the study of the variation of the ARR with the twist angle (for the radial component of the velocity) are shown in Fig. 8. The dotted lines show the approximation curve corresponding to the centred flow from the outlet absorber without the axial component, and the solid line shows the changes in ARR with a flow tilt towards the main absorber of 10°. All curves are well approximated by a third degree polynomial. At mass flow rates of 0.21 kg/s for the geometry of the small absorber, the flow twist initially has no effect on the ARR value, and for values of the radial component less than 0.7 (tangential component greater than 0.45) it reduces the ARR. At a mass flow of 0.16205 kg/s (designed mass flow), an almost constant ARR value is observed for values of the radial component greater than 0.8 (tangential velocity component less than 0.57). At low mass flow rates of 0.12 kg/s, vortexing the flow with a value of the radial component = 0.7 increases the ARR to 1 %.

Similar values were obtained for a large receiver design, where for a mass flow of 2.43 kg/s a value of 0.5 for the tangential velocity component increased the ARR by 0.95 %. In all cases, a 10° inclination of the outlet air to the main absorber increases the ARR.

Since a high tangential component of the return air through the outlet absorber reduces the kinetic energy, too high a value of this component causes the lift forces (created by the density difference between the warm air and the environment) to be greater than the suction forces (created by the system fan). This explains the existence of an extremum in the functional dependence of ARR on the tangential/radial velocity component. The creation of a highly turbulent flow in the centre of the receiver, although it redistributes the inlet flow to the lower part of the receiver, also increases the area of backflow, which has a negative

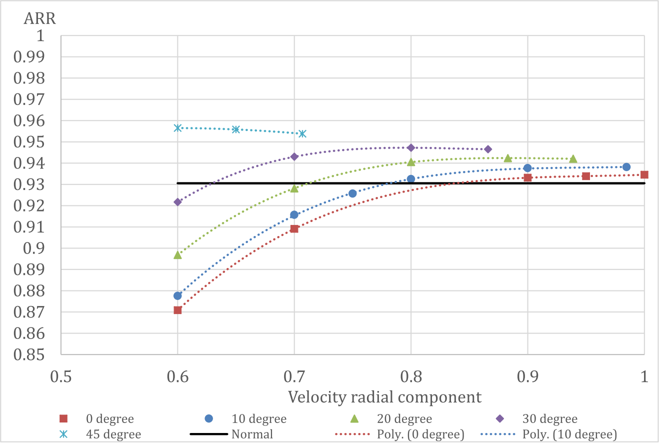

Fig. 11. Dependence ARR for different velocity components in VoCoRec small size for m = 0,21 kg/s.

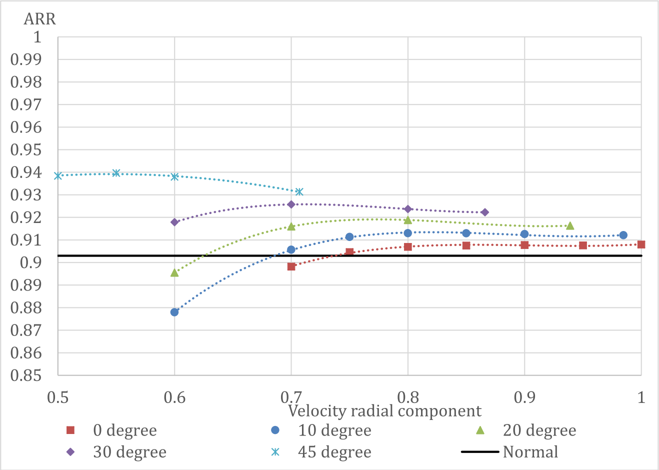

Fig. 12. Dependence ARR for different velocity components in VoCoRec small size for m = 0,162 kg/s.

effect on the ARR (Fig. 9).

By comparing the air velocity fields in the receiver for different mass flow rates with and without vortex flow, it was concluded that the line of zero velocity gradient (flow separation line between green and blue color) shifts toward the receiver opening with vortex flow. Comparing the air pressure fields in the receiver for different mass flow rates with and without vortex flow (Fig. 10), it was concluded that the pressure drop zone does not change with vortex flow. This is due to the fact that the pressure drop zone depends only on the mass flow rate and the geometry of the receiver, making this parameter useful for geometry optimization.

Figs. 11 and 12 show the dependence ARR for different velocity components in a small size VoCoRec for different mass flow rates. The solid black line shows the ARR value for the normal velocity distribution of the outlet flow from the outlet absorber (absorber type - grid). The smaller the radial component of the velocity, the larger the tangential component (i.e., the angle of the vortex flow).

As the angle of inclination of the air from the outlet absorber increases (increasing the absolute value of the axial velocity component) to the main absorber, the ARR will increase as the air is directed deeper into the receiver.

It is expected that the optimal feed angle depends on the geometry of the receiver, namely the ratio of its depth to the diameter of the main absorber. For the geometry under consideration, this ratio is 380/350. The distance between the center of the main absorber and the far point on the receiver aperture is 424 mm, with an angle of inclination of this curve to the receiver symmetry axis of 32°.

Also Figs. 11 and 12 show the ARR dependence for an axial angle degree. In addition to the general trend of increasing ARR with increasing the axial angle of the outlet air from the outlet absorber, some conclusions can also be drawn. As the air flow rate through the receiver decreases, the effect of the axial angle on the ARR increases. The ARR dependence for different velocity components in VoCoRec can be described by a linear approximation with a minimum root mean square determination coefficient of 0.977, or by a third-degree polynomial with a minimum root mean square determination coefficient of 0.995. It was also found that the smaller the mass flow rate for a fixed geometric size, the higher the degree of polynomial dependence (for VoCoRec Large with a mass flow rate of 2.43 kg/s, the polynomial dependence is described by a 6th degree polynomial with a determination coefficient of 0.758).

At a large angle of inclination (45°), the type of ARR dependence for different velocity components changes and an increase in the vortex flow angle increases the ARR more strongly.

To achieve a positive effect of increasing the ARR, it is recommended to have an axial angle of inclination of the outlet air of 30–45° with a vortex angle of 15–30°. The maximum effect of increasing the ARR occurs at an axial angle of inclination of 45°, with a vortex flow angle of 22° (axial velocity component $= -0.707$, tangential velocity component $= 0.374$, radial velocity component $= 0.6$).

5. Conclusions

This work establishes that generating a regulated output air vortex can raise the air return ratio in a VoCoRec receiver. For the VoCoRec small planned geometry, an increase in ARR of 4 % was obtained at the nominal mass air flow rate.

The primary conclusions that came from the computer modeling and computations were as follows:

There exists an optimal flow out angle of return air that depends on the receiver's geometry and mass flow (Figs. 11 and 12).

- increasing the angle of inclination (axial velocity component) of the air from outlet absorber in the direction of the main absorber increases the ARR, but the effect from vortex decreases;
- as the mass velocity decreases, the effect of uniform flow distribution from the vortex decreases;
- for large unit of VoCoRec with the mass flow rate of 2.43 kg/s and the value of the tangential velocity component of 0.5 (radial component $= 0$) the ARR increases by only 0.95 %.

Generally speaking, creating a vortex inside the hollow receiver's plane can decrease convection losses with air while simultaneously stabilizing the flow, which in theory raises the absorber's resistance to outside wind. The creation and improvement of this research include examining the impact of the swirling flow inside the hollow receiver on counteracting variations in the receiver's efficiency at various external wind directions and speeds. The investigation of non-design conditions of the cavity receiver with a vortex and the impact of surrounding wind on the vortex's stability are the main areas of future research.

CRediT authorship contribution statement

Andrii Cheilytko: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization. **Peter Schwarzbözl:** Writing – review & editing, Writing – original draft, Project administration, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The team of authors would like to express their gratitude to the DAAD (German academic exchange service), thanks to which the team that conducted this research was formed. Our team would also like to thank Kai Wieghardt from DLR for his support and inspiration.

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