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**Doi: 10.53412/jntes-2023-2-2**

# A NEW IDEA TO INCREASE THE CONVECTIVE EFFICIENCY OF A SOLAR TOWER AIR RECEIVER BY CREATING A CONTROLLED VORTEX

***Abstract:*** *Concentrated solar energy as a source of renewable energy has a high potential for solving the current energy crisis. The solar tower receiver is a crucial element of solar energy conversion efficiency. To increase the convective efficiency of the solar tower receiver, the idea of creating a vortex is proposed. The vortex is created either in the plane in front of the receiver, for flat receivers, or in the internal volume of the receiver, for cavity-type receivers. The calculation formulas for calculating the parameters of the controlled vortex are proposed and computer modeling is performed to determine the effectiveness of the proposed idea. The results of computer modeling confirmed the physical possibility of the controlled vortex formation in the receiver space and visually show the flow structure. Also, the general dependence of the air return coefficient in the VoCoRec receiver on the flow twist was found. Conclusions are drawn on the satisfactory results obtained and on the improvement of the existing model of the controlled vortex.*

***Keywords:*** *receiver, solar tower, convective efficiency, vortex, modeling, air return ratio*

## Introduction

Solar energy is widely used for the production of low potential heat and for the production of electricity. In the first case, flat solar collectors are used that do not concentrate (coolant – water, air, antifreeze). In the second – electricity from the light flux can be produced in two ways: by direct conversion in photovoltaic installations or by heating the coolant, which performs work in a thermodynamic cycle. Concentrated solar power plants (CSP) are used to use high potential thermal energy.

Energy and exergy efficiency of different CSP elements (turbine, generator, pumping group) is above 90%. The energy efficiency of the receiver does not reach 90%, and the exergy efficiency is at best 60%. Therefore, it is possible to achieve the highest efficiency with the lowest economic investment by improving the CSP receiver technology.

The efficiency of the receiver in a stationary process depends only on the ratio of changes in the thermal energy of the fluid to the supplied solar energy. This formulation of the problem allows to calculate the overall efficiency of the receiver, but does not allow to optimize its structure. Therefore, for the problem of improving the structure of the receiver, it is necessary to adhere to the following initial factors of the model: efficiencies based on receiver spillage; efficiencies based on receiver absorption; efficiencies based on receiver radiation; efficiencies based on receiver convection; efficiencies based on receiver conduction.

In this article, we propose to consider the idea of increasing the efficiency based on receiver convection in open-type receivers of solar towers by creating a controlled vortex.

## Literature revive

As a rule, the efficiency of the receiver is found by the numerical model without dividing it into components [1, 2]. But this approach does not make it possible to analyze the dependent factors of influence on the receiver of the solar station, so for the modeling of the receiver it is considered as its indicators. The efficiency of an open receiver as the efficiency of its elements [3]. According to this approach, the convective losses of the receiver will be determined separately from other components of the thermal efficiency of the solar tower receiver.

The problem of warm air leakage from the tmp cavity receiver has been known since the end of the last century [4]. But for the first time a broad overview of 18 proposals to reduce warm air leakage with an assessment of these measures appeared in 2014 in the work of J. Grobbel [5]. The idea of barrier flow is to prevent hot air from leaving the opening and cold air from entering it, and can be compared to an air curtain on a building door. One idea is to blow to cancel the existing vortex in the receiver. Another is to introduce an additional vortex, and so on. At the same time, the author did not consider the idea of creating a controlled vortex with specific sealing characteristics that will depend on the mass.

Among the modern works that investigate the problems of increasing the air return coefficient, it is worth noting the works of [6-9] which consider both analytical and practical methods for calculating heat losses with exhaust air, as well as the dependence of the air return coefficient on the angle of the receiver to the horizon. However, none of these studies considered the possibility of increasing the convective efficiency of the receiver by creating a controlled vortex. Therefore, the idea of creating a controlled vortex is considered new and is discussed in more detail in this article.

## Theory and calculation

To understand the cause of air leakage, it is necessary to consider its aerodynamics. The relationship between the velocity and pressure field is described by the Navier-Stokes equations [10]

$$\nabla\left(-p+\mu\left(\nabla w+\left(\nabla c w^{T}\right)\right)\right)=\rho\left(w\nabla\right)w \tag{1}$$

where:
$w$ – speed.

The optimal configuration of the receiver cannot be calculated separately and is considered in conjunction with other parts of the solar tower [11]. Therefore, consider the balance of the receiver as a block with input and output parameters. Considering the energy balance of the air circuit of a solar tower with an open porous receiver, it is possible to write down the direct circuit efficiency

$$\eta_{rec}^{air}=\frac{Q_{use}^{air}}{I_{rec}} \tag{2}$$

where:
$Q_{use}^{air}$ – the heat energy transferred from the primary air heat transfer medium to the next circuit is defined as the difference in enthalpy between the air at the inlet and outlet of the heat exchanger or reactor in which the energy is transferred, kW;

and inverse balance

$$\eta_{csp}^{air}=\frac{I_{mirror}-Q_{loss}^{air}-Q_{refl}^{rec}-Q_{emi}^{rec}-Q_{h.tr}^{CSP}-Q_{loss}^{mirror}-W_{fan}}{I_{mirror}} \tag{3}$$

$$I_{mirror}-Q_{loss}^{air}-Q_{refl}^{rec}-Q_{emi}^{rec}-Q_{h.tr}^{CSP}-Q_{loss}^{mirror}=\Delta H_{f} \tag{4}$$

where:

$Q_{loss}^{air}$ – energy loss with the physical heat from the air leaving the solar plant to the environment, kW;

$Q_{refl}^{rec}$ – energy loss by reflection of solar radiation in the porous absorber into the environment, kW;

$Q_{emi}^{rec}$ – energy loss by emission (convective and radiation losses) in the porous absorber to the environment, kW;

$Q_{h.tr}^{CSP}$ – heat loss from the air circuit surface of the solar tower pipe and heat exchange to the environment, kW;

$Q_{loss}^{mirror}$ – losses of solar energy from uneven arrival of solar radiation from mirrors, kW;

$W_{fan}$ – power for internal air circuit needs, in the simplest case this is fan operation, kW;

or in relative terms

$$\eta_{csp}^{air} = 1 - q_{loss}^{air} - q_{refl}^{rec} - q_{emi}^{rec} - q_{h.tr}^{CSP} - q_{loss}^{mirror} - K_w \tag{5}$$

this

$$q_{loss}^{air} = \frac{Q_{loss}^{air}}{I_{mirror}}; \quad q_{emi}^{rec} = \frac{Q_{emi}^{rec}}{I_{mirror}}; \quad q_{h.tr}^{CSP} = \frac{Q_{h.tr}^{CSP}}{I_{mirror}}; \quad q_{loss}^{mirror} = \frac{Q_{loss}^{mirror}}{I_{mirror}}; \quad K_w = \frac{W_{fan}}{I_{mirror}} \tag{6}$$

Energy loss with the physical heat from the air leaving the solar plant to the environment, kW

$$Q_{loss}^{air} = \left(H_{loss}^{air} - H_{amb}^{air}\right) \cdot \left(1 - ARR\right) \cdot \varepsilon \tag{7}$$

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;

$\varepsilon$ – a delay factor related to the time required to heat the exhaust air to a given temperature, for the stationary case = 1.

Considering that the ratio of receiver air losses is directly proportional to the change in *ARR*, ceteris paribus, energy losses with air

$$\frac{Q_{loss}^{air}|_{ARR1}}{Q_{loss}^{air}|_{ARR2}} = \frac{1 - ARR|_1}{1 - ARR|_2} \tag{8}$$

$$Q_{loss}^{air}|_{ARR2} = Q_{loss}^{air}|_{ARR1} \frac{1 - ARR|_2}{1 - ARR|_1} \tag{9}$$

The efficiency ratio can be written as

$$\frac{\eta_{conv}|_{ARR1}}{\eta_{conv}|_{ARR2}} = \frac{\Delta U_{rec} + \Delta H_f + Q_{loss\_en} + Q_{loss}^{air}|_{ARR2}}{\Delta U_{rec} + \Delta H_f + Q_{loss\_en} + Q_{loss}^{air}|_{ARR1}} \tag{10}$$

Therefor

$$\frac{\eta_{conv}\left|_{ARR1}\right.}{\eta_{conv}\left|_{ARR2}\right.}=\frac{1+\dfrac{\eta_{cond}Q_{loss}^{air}\left|_{ARR2}\right.}{I_{mirror}\eta_{rec}^{air}}}{1+\dfrac{\eta_{cond}Q_{loss}^{air}\left|_{ARR1}\right.}{I_{mirror}\eta_{rec}^{air}}} \tag{11}$$

$$\frac{\eta_{conv}\left|_{ARR1}\right.}{\eta_{conv}\left|_{ARR2}\right.}=\frac{1+\dfrac{\eta_{cond}Q_{loss}^{air}\left|_{ARR1}\right.\dfrac{1-ARR\left|_{2}\right.}{1-ARR\left|_{1}\right.}}{I_{mirror}\eta_{rec}^{air}}}{1+\dfrac{\eta_{cond}Q_{loss}^{air}\left|_{ARR1}\right.}{I_{mirror}\eta_{rec}^{air}}} \tag{12}$$

$$\frac{\eta_{conv}\left|_{ARR2}\right.}{\eta_{conv}\left|_{ARR1}\right.}=\frac{1+q_{loss}^{air}\left|_{ARR1}\right.\cdot\dfrac{\eta_{cond}}{\eta_{rec}^{air}}}{1+q_{loss}^{air}\left|_{ARR1}\right.\cdot\dfrac{\eta_{cond}}{\eta_{rec}^{air}}\cdot\dfrac{1-ARR\left|_{2}\right.}{1-ARR\left|_{1}\right.}} \tag{13}$$

$$q_{loss}^{air}\left|_{ARR1}\right.\left\langle 1,\frac{\eta_{cond}}{\eta_{rec}^{air}}\right\rangle 1 \tag{14}$$

To determine the change in the convective efficiency of the swirling efficiency flow, a computer simulation of the VoCoRec receiver was performed. The twisting process for each face of the receiver is shown in Figure 1.

Each kg of dry air contains 125.98 kJ/kg of energy at 5 bar and 150°C and 832.48 kJ/kg at 800°C [12]. Achieving an *ARR* from 0.6 to 0.9 allows the system to feedback approx. 38 kJ/kg of energy. The practical target for improvement of the new model is to achieve an *ARR* above 0.9, therefor $q_{loss}^{air}|_{ARR=0.9} = 0.05$. A modern model of an absorber like VoCoRec allows for an *ARR* of 0.9. For a typical calculation of the energy efficiency of a solar tower with volumetric receiver of open type, it is customary to take $I_{mirror} = 1000\ \mathrm{kW/m^2}$ flux density in the aperture plane and 800°C hot air temperature [13], $\Delta H_f = 1000$ kJ/kg [14-16].

If

$$\frac{\eta_{cond}}{\eta_{rec}^{air}}=1.125$$

then

$$\frac{\eta_{conv}\left|_{ARR2}\right.}{\eta_{conv}\left|_{ARR=0.9}\right.}=\frac{1.05625}{1+0.05625\cdot\dfrac{1-ARR\left|_{2}\right.}{0.1}} \tag{15}$$

Therefore, an increase of *ARR* from 0.9 to 0.95 will increase efficiency by 1.027 times.

There are a number of studies dedicated to the study of cyclone devices: studies of methods for determining the resistance coefficient, studies of methods for determining the angle of twist, studies of methods for determining the zone of reverse currents [17, 18].

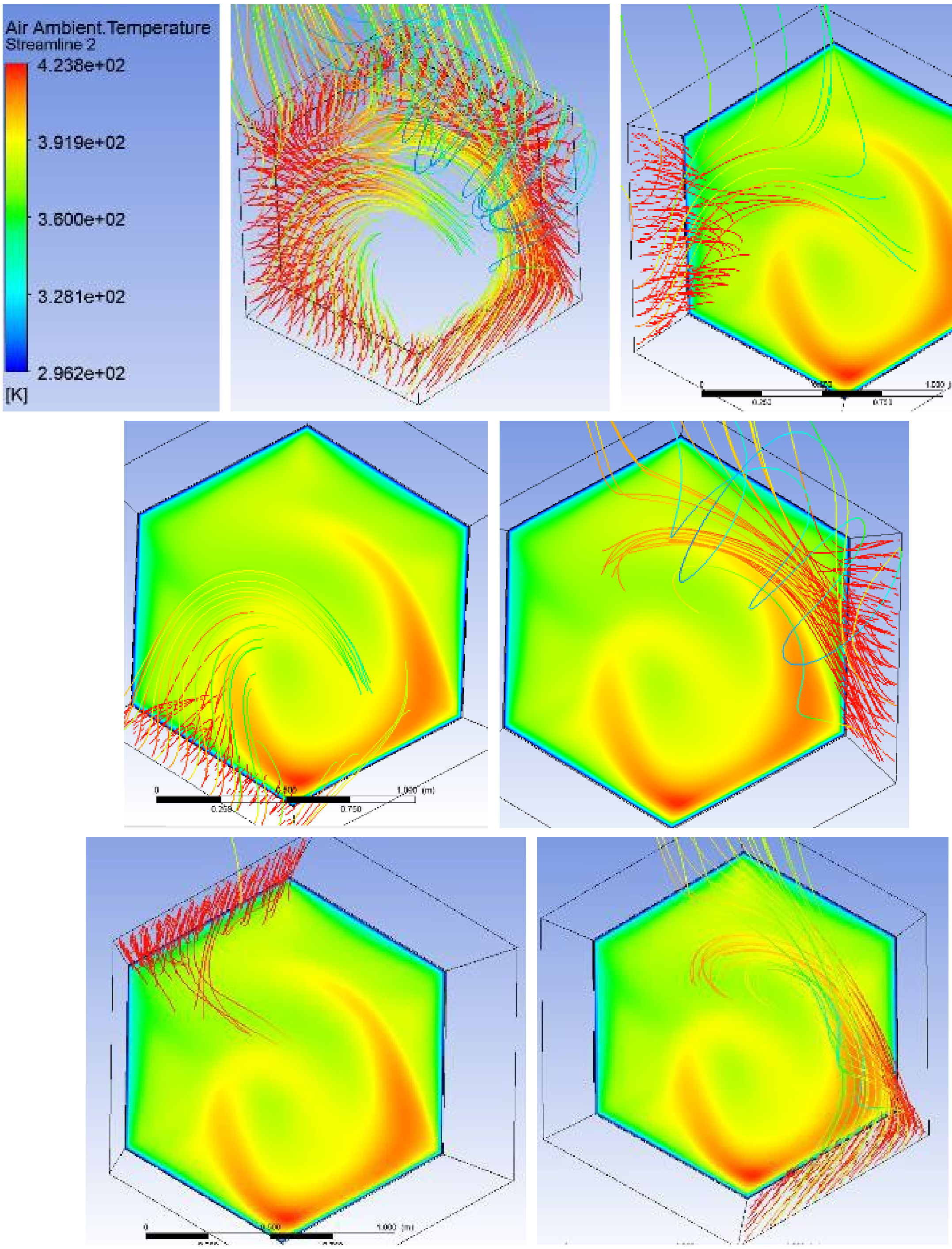

***FIGURE 1.*** *Temperature distribution along current lines for swirling flow in VoCoRec Large mass Flow 2.43 kg·s*$^{-1}$

Finding the zone of inverse currents is given in [17] where the vortex radius is proposed to be found from the "radius of twist of the flux" which is defined as

$$\alpha = \arcsin \sqrt[3]{\frac{\sum f_{BX}}{\pi \cdot R_n \cdot R_c \cdot \cos\beta \cdot \cos\gamma} \cdot \frac{1}{4\xi}} \tag{16}$$

where:

$\xi$ – the ratio of the initial momentum loss;

$\beta, \gamma$ – for a shovel-less certifier are assumed to be equal to zero;

$R_c$ – aerodynamic camera resistance;

$R_n$ – aerodynamic nozzle resistance.

Air output momentum

$$M_{out} = \int_0^{2\pi}\int_{R_V}^{R_{Out}} \rho_{out} W_{out}^2 \sin\alpha_1 \cos\alpha_1 r^2 dr d\varphi \tag{17}$$

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

$$\frac{R_B}{R_C} = 1 - \frac{\sum f_{BX}}{\pi \cdot R_K \cdot R_C \cdot \cos\beta \cdot \cos\gamma} \cdot \frac{1}{2\mathrm{tg}\alpha} \cdot \frac{1}{\xi} \cdot \frac{\rho_0}{\rho_1} \tag{18}$$

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

$$\xi = \frac{2\Delta P}{\rho w^2} \tag{19}$$

where:

$w$ – the average flow rate;
$\rho$ – the flux density at the same location;
$\Delta P$ – the difference between the pressure at the inlet and outlet of the swirl unit.

$$\xi\left(ARR = 1\right) \rightarrow \min \tag{20}$$

Decomposing the velocity vector into components we obtain

$$w^2 = c^2 + u^2 + v^2 \tag{21}$$

where:

$c$ – tangential speed;
$u$ – radial speed;
$v$ – axial speed.

Figures 2 and 3 show the temperature distribution of the swirling flow for different mass flow rates. From the figures, it can be seen that the mass flow rate affects not only the formation of the vortex in the aorta but also its uniformity of distribution.

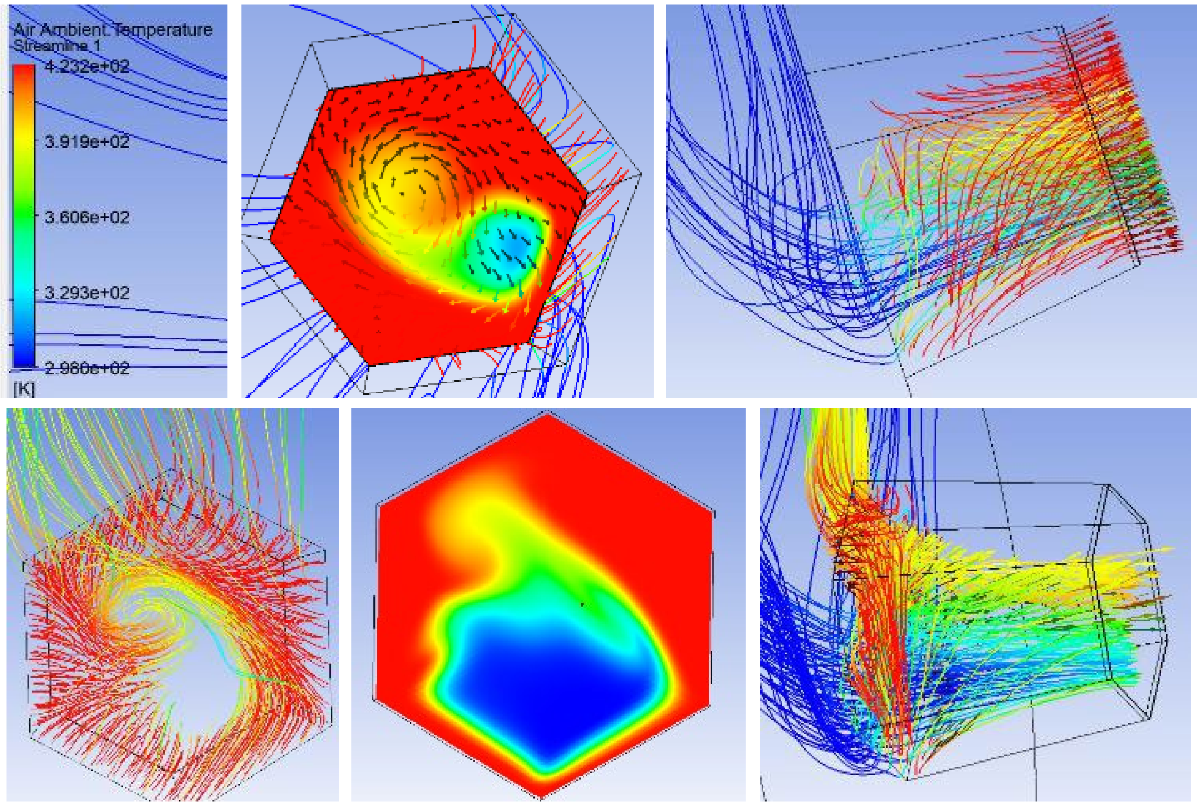

***FIGURE* 2.** *Temperature distribution along current lines for swirling flow in VoCoRec Large mass Flow 5.04017* $kg \cdot s^{-1}$

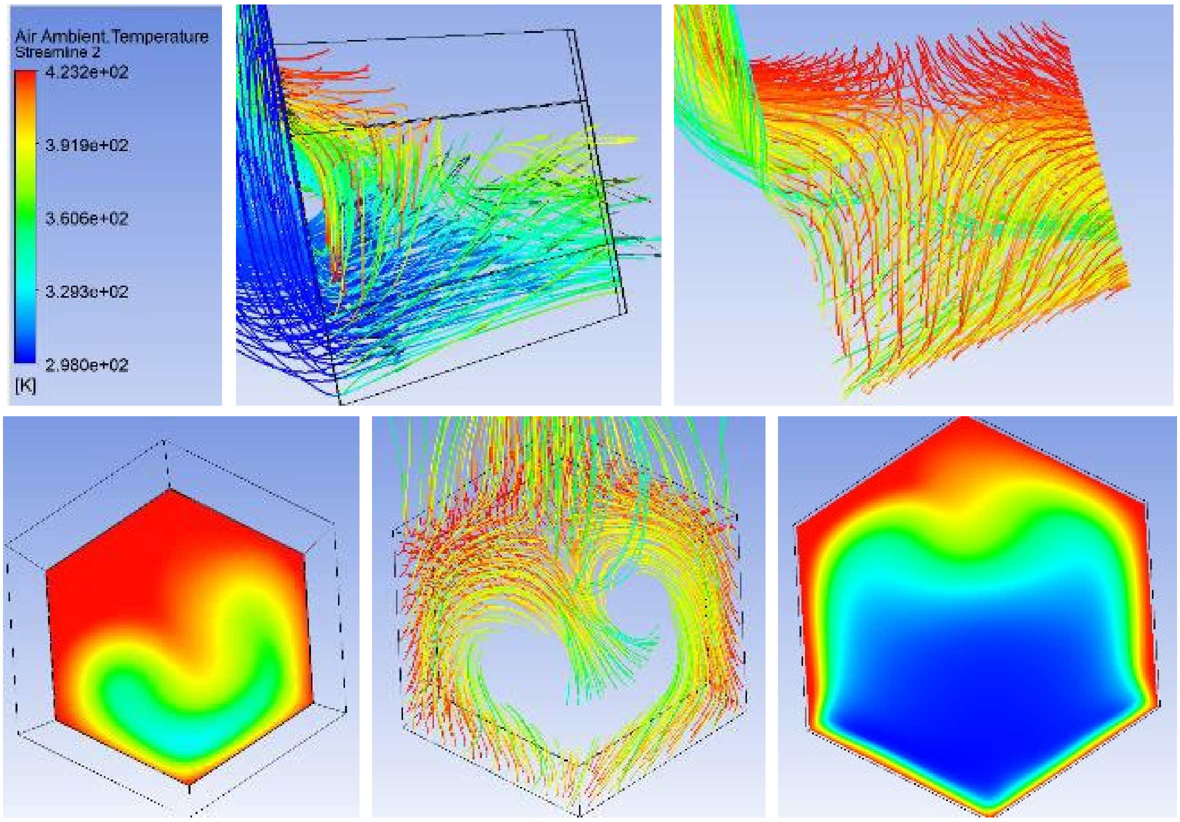

***FIGURE 3.*** *Temperature distribution along current lines for swirling flow in VoCoRec Large mass Flow 1.2 kg·s*$^{-1}$ *ARR = 0.7*

Boundary conditions for air by front absorber in the absence of traction forces to the main absorber, vector v of directions towards the main absorber

$$r \in \left(0; R_{abs}\right) \tag{22}$$

If

$$r \in \left(0; r_{in}\right)$$

then

$$\mathrm{grad}(\mathrm{P}) < 0,\ c > 0,\ v \to 0,\ v < 0$$

in the separated line:

if

$$r = R_V$$

then

$$v = 0;\ \mathrm{grad}(\mathrm{P}) = 0,\ c = 0$$

if

$$r = \left(R_V; R_{abs}\right)$$

then

$$\mathrm{grad}(\mathrm{P}) > 0,\ v > 0,\ c > 0,\ u > 0$$

It is proposed to find the function of aerodynamic resistance as well as the air return coefficient using computer modeling. The air return coefficient is calculated as the ratio of the air that exited the receiver and entered the main absorber to the total mass flow rate through the main absorber.

Comparing the air velocity fields in the receiver for different mass flow rates with and without flow swirl (Fig. 4), it was concluded that the line of zero velocity gradient (flow separation line) with flow swirl shifts to the receiver aperture.

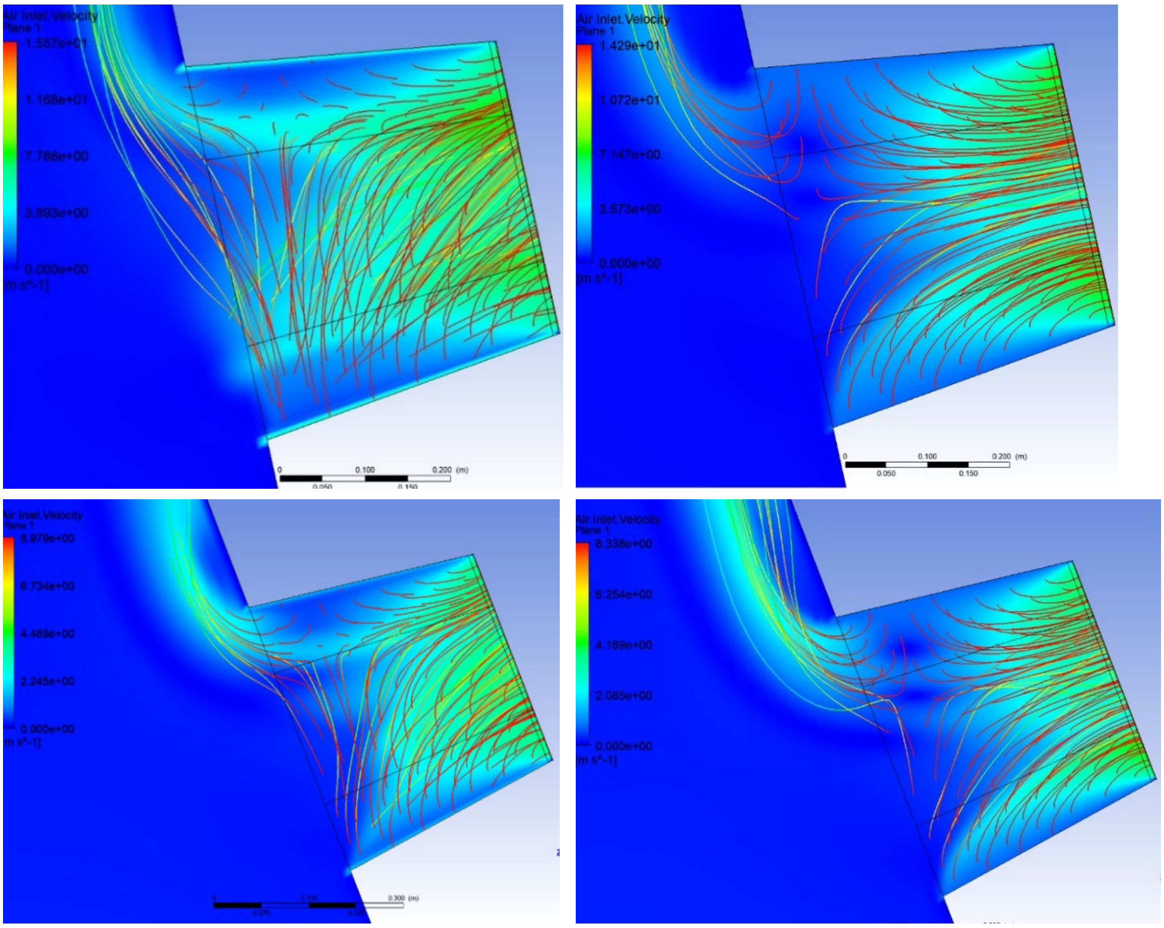

***FIGURE 4.*** *Air inlet velocity in VoCoRec small size with m = 0.21 kg·s$^{-1}$, VGR = 0.6, ARR = 0.871 (left up) and m = 0.21 kg·s$^{-1}$, VGR = 1, ARR = 0.935 (right up) and m = 0.12 kg·s$^{-1}$, VGR = 0.7, ARR = 0.872 (left down) and m = 0.12 kg·s$^{-1}$, VGR = 1, ARR = 0.87 (right down)*

The Figure 5 shows the distribution of air temperature near the front of the main absorber, which provides conditions for analyzing the occurrence of local overheating points.

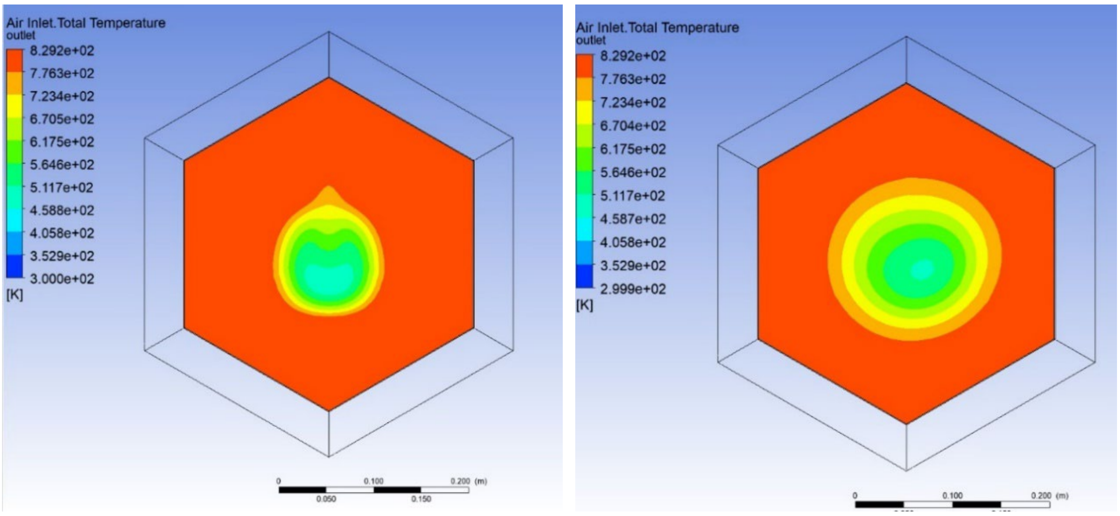

***FIGURE 5.*** *Air outlet temperature in VoCoRec small size with m = 0.21 kg·s$^{-1}$, VGR = 0.6, ARR = 0.871 (left) and m = 0.21 kg·s$^{-1}$, VGR = 1, ARR = 0.935 (right)*

Figure 5 shows that for a given mass flow rate, the air return coefficient decreased with the flow swirl, and the thermal drop across the main absorber increased. Although the flow was distributed more evenly, it created a cold spot in the center of the absorber due to the strong reverse flow zone.

Structurally, the swirling flow can be achieved by: tangential air supply or by installing guide vanes.

The change in *ARR* from a decrease in the radial component with an increase in the tangential component (i.e., stronger flow twist) for low mass flow is shown in Figure 6.

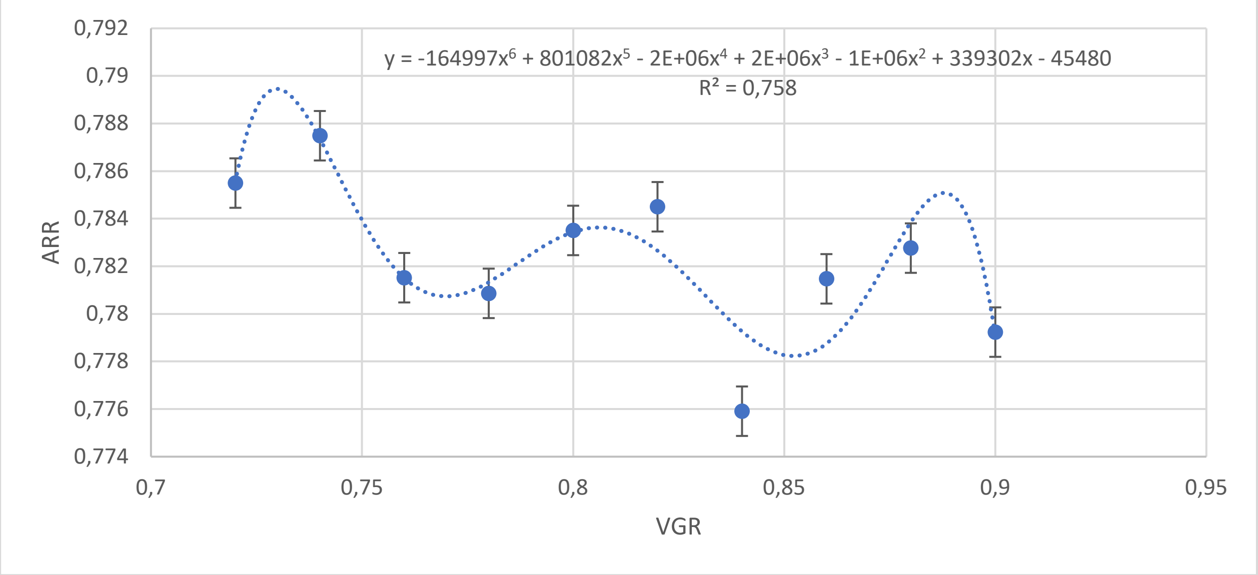

***FIGURE 6.*** *Dependence of ARR on the radial component of the vector gradient (VGR) in the flow direction 2.43 kg·s$^{-1}$ of the VoCoRec Large*

These results indicate a general tendency to increase the air return ratio, and hence the convective efficiency of the receiver when creating a controlled vortex. However, the results also show significant fluctuations in the *ARR* from the radial component of the air supply to the receiver zone caused by the high degree of turbulence.

## Conclusions

This paper considers the possibility of creating a controlled vortex in an open-type receiver of a solar tower. The basic solution dependencies are proposed and the vortex structure in the modeled flow is shown. In order to increase the convective efficiency of the receiver, it is necessary to reduce the aerodynamic drag of the receiver structure and to reduce the air return coefficient.

A high degree of dependence of the air return coefficient on the mass flow rate through the receiver has been confirmed. The polynomial dependence of the air return coefficient in the receiver on the radial component of the circulating air velocity is shown. It is proved that the existence of a vortex can have both positive and negative results. In order to develop an analytical model, it is proposed to conduct comprehensive studies of the dependencies of the air return coefficient on the components of velocity and mass flow rate.

Most importantly, the possibility of increasing the convective efficiency of the solar thermal receiver by 2% by creating a controlled vortex was confirmed.

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