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Analysis of the Thermal and Resistance Characteristics of a Fixed-Bed Regenerator for an Unsteady Flow and a Small D/dp Ratio

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Abstract

This inquiry focuses primarily on the unsteady flow that occurs within a fixed-bed regenerator and uses a three-dimensional computational fluid dynamics (3D CFD) simulation as its major method of data collection and analysis. For the goal of investigating the flow complexity and thermal properties of the regenerator, this study employed a fixed-bed regenerator with particle to diameter ratios (D/dp) of 3, 8, and 12 in order to conduct the investigation. Because of their low D/dp and the increasing vacancy ratio near the regenerator wall, these beds present significant challenges to the movement of material through them. This is in contrast to the bulk area, which presents less challenges. In order to conduct an inquiry into the complex flow dynamics that take place in these sites, the utilization of flow analysis software that is commercially available is required. It was found that the results of the predicted pressure drop and wall effect, in addition to the data from the preceding trials, were found to have a good agreement with one another. This was found to be the case when it was discovered that the findings had a good agreement with one another.

Index Terms - CFD; fluent, wall effect; regenerator; transient; Unsteady

INTRODUCTION

To make use of the waste heat that is created by flue gases, cutting-edge pieces of machinery like heat exchangers, recuperators, regenerators, heat pipe exchangers, rotary heat exchangers, economizers, and heat pumps are utilized. Other modern pieces of machinery that are used to make use of this heat include economizers. Economizers, heat pipe exchangers, and rotary heat exchangers are some of the other components that are included in this apparatus. The current inquiry focuses on the usefulness of using regenerative heat exchangers, which are also commonly referred to as regenerators, as a way of recovering heat from exhaust gases in industrial and commercial settings. This type of heat exchanger may be used in a variety of applications. A heat regenerator is a sealed container that is crammed full with numerously shaped metals or ceramics that are capable of amassing significant amounts of thermal energy and storing that energy for later use. This energy may be drawn from the heat regenerator when it is needed. The heat regenerator is able to store the energy that it absorbs so that it may be utilized at a later time. Recuperators are devices that allow the transfer of heat between two fluids that are physically separated by a wall. The wall acts as a barrier between the fluids. The wall creates a physical barrier that prevents the fluids from mixing with one another. Because there is a thin wall separating the fluids, there is no contact between the fluids due to the presence of the wall. This is because the wall is separating the fluids. In contrast, the fluid in a storage-type heat exchanger is expected to go through a solid bed that is designed to absorb heat from one fluid and transmit it to another fluid. The goal of this action is to transfer the heat from the first fluid to the second fluid. This is done so that the fluid may then transfer its heat to another fluid. In this case, the fluid in the storage-type heat exchanger will transfer the heat to the fluid in the next chamber. Because of this, it is possible for one fluid to transmit its heat to another fluid. Using a piece of equipment such as this heat exchanger, it is possible to transfer the heat from one fluid to another. Regenerators are the name given to heat exchangers of the particular type being discussed here within the industry. Heat is stored and transferred using devices known as regenerators. When beginning the process of creating a continuous operation, the utilization of two or more parallel fixed-bed regenerators is a required component. Because of the manner that this apparatus is constructed, there is a possibility that one bed may have cold gas flow through it, while another bed will have hot gas flow through it. Figure 1, which may be seen further down on this page, illustrates this configuration by use of two fixed-bed regenerators operating in tandem.

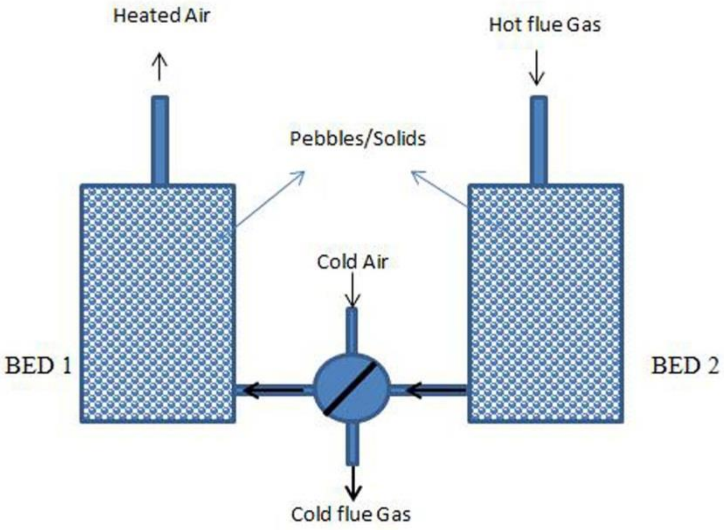

Fig. 1

Fixed bed heat regenerator

Literature Review

Pressure drop within regenerator

Ergun's equation, which can be found in reference, offers a forecast regarding the drop in pressure that will take place within the regenerator when there is a totally formed flow. This prediction may be obtained in the situation where there is a fully formed flow. This equation sets the condition that it can only be utilized for very large D/dp ratios (greater than 15), in which case it is needed to have homogeneity in the void percent. This constraint is imposed by the equation itself.

The Ergun’s equation is:

$$\frac{\Delta p}{H} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{d_p^2} + 1.75\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho U^2}{d_p} \qquad 1$$

Everyone has arrived to the same conclusion, which is that the coefficients of the equation that Ergun stated in Equation 1, which are 150 and 1.75, are disputable and open to discussion. It has been determined that this will be the situation. The coefficients in the equation that is provided in for the decrease in pressure that occurs in a fixed bed regenerator that uses spherical particles are not constant; rather, they are dependent on the Reynolds number. Ergun's equation was shown to be unable of accurately predicting the pressure that would be present in an irregularly packed bed regenerator in a separate piece of study that was carried out by. This was demonstrated via the use of a mathematical model. This was the conclusion reached as a result of the research. As a consequence of the outcomes of the research that was discussed before, this was the conclusion that was arrived at. The following is an extra equation that is provided by reference number , which may be used to calculate the pressure drop that occurs within the fixed bed regenerator. This equation, which is quite close to Eq. 2, has the following form:

$$\frac{\Delta p}{H} = 180\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu U}{d_p^2} + 1.8\frac{1-\varepsilon}{\varepsilon^3}\frac{\rho U^2}{d_p} \qquad 2$$

All of the calculations for pressure that have been addressed up to this point apply to fixed bed regenerators with D/dp values that are more than 15, since these values have been assumed throughout all of the calculations. The level of flow complexity in these scenarios is quite low due to the fact that regenerators with D/d values greater than 15 are believed to have a constant void percent in the bed. This is due to the fact that the bed maintains a constant amount of vacuum space throughout its whole.

These beds have a high level of flow complexity because there is a greater amount of unoccupied space at the regenerator wall than there is in the bulk area of fixed beds with low D/dp 10. This difference is due to the fact that the regenerator wall is located at an angle. An very advanced flow analysis tool, such as Ansys Fluent, is necessary in order to offer a full knowledge of the flow structure in regions that are geographically close to the particles that make up these beds. This is so that the flow structure can be accurately modeled. This tool is essential for providing a comprehension of the flow structure and is thus necessary.

The extensive investigation on the wall effects in regenerators that was published in reveals that the correlation for pressure reduction that was offered by is the most promising one. This was demonstrated by the fact that was cited as the source. The reference number was given as the origin of this information.

Utilizing CFD simulations for the purpose of determining the pressure drop and drag coefficients for fixed beds with D/dp values that are less than 10, and then comparing the values to the pressure drop and drag coefficients for variable beds. results with, is one of the primary goals of the work that is currently being done. This is one of the primary goals of the work that is currently being done. One of the most important objectives of the work that is now being done is to achieve this.

Flow regimes in Fixed bed regenerator

The many flow regimes that are present within a regenerator have a significant impact on the resistance and thermal qualities that are accountable for defining how well the regenerator will do its job. This is because the resistance and thermal characteristics are responsible for how well the regenerator works. This is because the resistance and thermal characteristics are responsible for how well the regenerator works. This is due to the fact that the resistance and thermal properties are crucial for determining how well the regenerator functions. Only fully developed flows are found to be compatible with Ergun's equation, and a large number of other researchers have investigated how the influence of walls on pressure drop in regenerators varies depending on the flow regime. Ergun's equation finds that only fully developed flows are compatible with it. To begin, the only flows that can be adequately described by Ergun's equation are those that have fully developed. Both and made predictions about the effects of wall borders when it came to creeping flow regimes. had similarly predicted that there would be a drop in pressure for the scenario that involved D/dp 4 and Reynolds numbers 100–1000. Creeping flow regimes had also anticipated that there would be a fall in temperature. In this work, estimates of the wall effects within the regenerator are presented for low values of D/dp<12 and for all flow regimes. These estimates are supplied regardless of the flow conditions (creeping, transition, and turbulent flow). These properties correspond to a range of Re values that goes all the way up to 10000 and stretches from 0.1.

In order to investigate the manner in which the temperature changes along the length of the regenerator bed, a model of the regenerator has been developed in Ansys Design Modular. The purpose of this inquiry is to determine how the temperature varies along the length of the regenerator bed. The model is then exported for transient simulation in Ansys Fluent with the following settings once it has been suitably meshed in GAMBIT: for regenerators with D/dp 3, 8, and 12, respectively, an increment of time equal to 10e-3, a switching time or cycle duration equal to one minute The transient CFD modeling of flue gases will continue for as long as it is necessary in order to reach a steady state in the temperature flow. This modeling will take place during the heating cycle when flue gases are present, and it will take place during the cooling cycle when ambient air is present. This is done in order to achieve a situation in which there is no discernible change in the flow of temperature.

Modeling CFD

The use of computational fluid dynamics is a vitally important new method that has been increasingly popular in recent years for addressing complex problems involving fluid mechanics and heat transfer. These problems can be difficult to solve because they include the transfer of heat (CFD). Recent research has shown that computational fluid dynamics, more commonly referred to as CFD, is a method that is extremely helpful, advantageous, and successful when it comes to predicting the flow and temperature distribution for challenging geometries. CFD is an acronym that stands for computational fluid dynamics. Researchers have reaped a number of benefits as a result of the capability of computational fluid dynamics (CFD) to carry out simulations or assessments by modifying the material features and geometries and assessing the effects of these changes on performance. One of these benefits is that researchers have reaped a number of benefits as a result of the capability of computational fluid dynamics (CFD) to carry out simulations or assessments. One of these advantages is the fact that CFD has made it possible for researchers to carry out simulations or evaluations. The computational fluid dynamics (CFD) software called "FLUENT," which forms the foundation of the current work, is widely recognized as being among the most dependable CFD systems. This is because the software was developed by NASA. An innovative piece of software called Ansys Fluent is used on modern personal computers to undertake simulations of heat transfer and fluid flow in intricate engineering environments. These simulations may be carried out in a variety of different scenarios.

Problem formulation for CFD simulation

The study that is being detailed here makes use of fluent in order to do an analysis of the fixed bed regenerator by applying the D/dp 12 formula. In contrast to the mathematical model and other simulation methodologies, which are unable to adequately evaluate such flow complexity, Fluent is able to do so successfully. This is one of the many advantages of using Fluent. This is due to the non-uniformity in the voidage that exists between the region near the regenerator wall and the bulk region of the regenerator. The bulk region is located farther away from the regenerator wall. The bulk region is situated further from the regenerator wall than the surrounding regions. Fluent has the capability of providing an accurate assessment of the complexity of flows of this kind.

Physical model, Computational geometry & meshing

Figure 2 displays how the physical model that was used as part of this investigation was put to use in order to analyze the transient flow and temperature pattern that was present across the regenerator bed for D/d values of 3, 8, and 12. Table 1 contains the specific geometrical information pertaining to the physical mode.

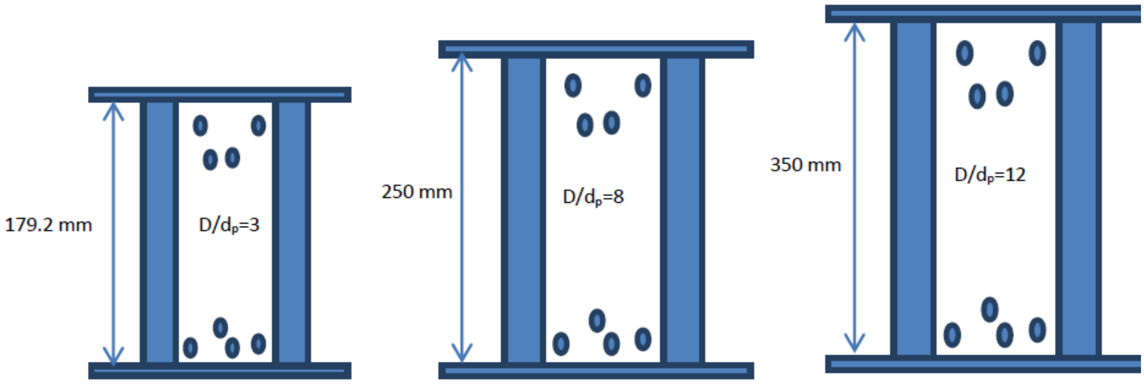

Fig. 2

Schematic of physical models of different bed heights and D/d_pratio

During each and every stage of the process of constructing the computational model, the Gambit program, which is a pre-processor for the Fluent program, was applied. It is utilized in the process of manufacturing the meshes as well as the geometries in their individual production procedures in order to get the desired results. Ansys ICEM was utilized so that the regenerator model that had been constructed with design modeler could be meshed. In order to obtain a precise portrayal of the impact of stratification within the regenerator, the process of meshing utilized 101332 hexahedral cells with 102445 nodes. This was done so that the effect could be accurately shown. Figure 3 illustrates a view of a variety of meshes that may be viewed when ICEM is used.

Table 1

Geometrical details of Physical models

Parameters	Physical Model		
	$D/d_p=3$	$D/d_p=8$	$D/d_p=12$
Average voidage/ porosity	0.439	0.439	0.439
Regenerator Diameter, mm	76.3	201.2	301.8
Regenerator height/ Bed height, mm	179.2	250	350
Particle/Solid Diameter, mm	25.15	25.15	25.15
Particle material	Aluminium refractories		

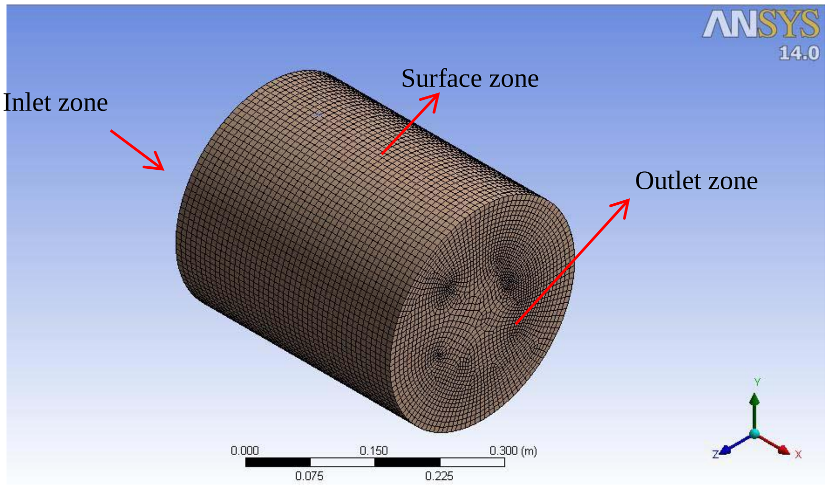

Fig. 3

ICEM view of surface meshing

The standard of the mesh that is employed in the CFD simulation analysis is vitally required if it is to deliver accurate findings in the smallest period of time that is practically possible. Taking a measurement of the skewness of the mesh is one of the most significant phases in establishing the overall quality of the mesh. This step is one of the most critical procedures. This is among the most crucial stages of the process. The degree to which the mesh has been twisted is referred to as its skewness. The degree to which a grid is skewed might give useful information on not just the grid's quality but also the application for which it will be used.

The value of skewness can be anywhere from 0 all the way up to 1 without going beyond that range. In hexahedral cells, the value of 0.85 ought to be regarded as the utmost permissible level of skewness that may be accepted at any cost. The current geometrical model has a skewness factor that ranged from 0.10 to 0.54 at its worst, with 0.10 serving as its average value. This number was determined by the standard deviation of the model. The table that follows displays the range of values for this factor. After being broken down into their individual parts, the two computational models' skewness factors are presented in Table 2, where they were computed using the results of the disassembly process.

Table 2

Skewness factor for regenerator bed modelled geometries

Parameters	Computational Model (transient model)		
	$D/d_p=3$	$D/d_p=8$	$D/d_p=12$
Total number of elements	77280	87216	101332
Element type	Hexahedral	Hexahedral	Hexahedral
Max. Skewness	0.55	0.54	0.54
Min. Skewness	1.4e-2	6.06 e-3	8.1e-03
Average Skewness	0.11	0.11	0.10

The aspect ratio is another statistic that may be used in the process of analyzing the quality of the meshing. It is an important factor to take into consideration. The "aspect ratio" of a cell is the relationship between the lengths of its longest side and its shortest side. This relationship is indicated by the phrase "aspect ratio." If we were in a perfect world, the following would be true: 1. The various factors pertaining to the aspect ratio that are necessary for computational models may be found in Table 3.

Table 3

Aspect ratio for regenerator bed modelled geometries

Parameters	Computational Model (transient model)		
	$D/d_p=3$	$D/d_p=8$	$D/d_p=12$
Min. aspect ratio	1.07	1.01	1.01
Max. aspect ratio	2.94	4.24	6.17
Average aspect ratio	1.62	1.55	1.73

An investigation of grid independence is now being carried out in a packed bed regenerator with mesh widths ranging from 0.5 millimeters to 1, 2, 3, and 4 millimeters. When the grid size is dropped from 5 millimeters to 4 millimeters, there is a corresponding reduction in pressure that falls somewhere in the range of 0.00356 Pa to 0.00358 Pa. This reduction in pressure is due to the fact that the grid size is directly proportional to the pressure. When the grid size is lowered from 3 millimeters to 2 millimeters, there is a drop in pressure of 0.00361 Pa; when it is dropped from 2 millimeters to 1 millimeter, there is a drop in pressure of 0.00361 Pa; and when the mesh size reaches 1 millimeter, there is a drop in pressure of 0.00361 Pa. However, there is no visible difference in the pressure drop even when the grid size is reduced to 0.5 millimeters. This would suggest that the Below a grid size of one millimeter, there is no correlation between the mesh size and the pressure drop. as was stated in the preceding statement. This would be the case if the grid size was less than one millimeter. The following simulation was carried out with a grid resolution of one millimeter because this was the direct result of the previous one.

A set of definitions for the boundary conditions that are suitable for the simulations may be found as follows:

- At the inlet zone, the following parameters were specified: inlet velocity (Re = 0.1 to 10000), inlet flue gas temperature (1473K), and air temperature (300K).
- At the border of the outlet, the zero-gauge pressure setting was specified.
- The material type was described for the zones that corresponded to it in the design modeler, and those zones were designated as fluid types.

- Within the cell zone condition dialog box, the porous zone option was activated for the porous medium model. Table 5 presents the information that you need to know regarding viscous resistance and inertial resistance.
- The fluid porosity level was maintained at 0.439.
- The wall surface of the regenerator was taken into consideration to be insulated.

RESULT & DISCUSSION

The difference in pressure that exists between the top and bottom of the bed that the regenerator rests on is referred to as the "pressure drop within the regenerator," and it is referred to by this name as well. In other terms, the pressure drop refers to the difference in pressure that exists between the top and bottom of the bed. Since the goal of this research is to examine the consequences of creeping, transitional, and turbulent flow regimes, a simulation of pressure drop is now being carried out. This shows that the simulation is carried out throughout the entirety of the potential value range for Re, which extends from 0.1 to 10000, and across the entirety of the available value range for D/dp, which extends from 3, 8, and 12 respectively. The particulars of the geometric model are laid out for your consideration in Table 6, which you may get here.

Table 6

Geometrical Models for the Regenerator in Preparation for CFD Analysis

Parameters	D/d_p= 3	D/d_p= 8	D/d_p= 12
Average Voidage / Porosity	0.439	0.439	0.439
Regenerator Dia. (mm)	76.3	201.2	301.8
Particle Dia. (mm)	25.15	25.15	25.15
Regenerator length, (mm)	179.2	250	350
Mesh	Hexahedral	Hexahedral	Hexahedral
Mesh size, (mm)	1	1	1

Transient CFD Analysis:

Flue gases are forced to enter the regenerator bed at a high temperature so that the simulation can begin, and they are required to remain in that location throughout the entirety of a cycle that lasts one minute (1473 K). After the heating cycle has finished its run, the cooling cycle will start up and get underway. This cycle will run for one minute and will entail air from the environment with a temperature of 300 degrees Kelvin entering the regenerator in the opposite direction. Flue gases must be allowed to flow during the heating cycle, while air from the surrounding environment must flow during the cooling cycle. This pattern of flow must be maintained until the temperature flow achieves its steady state, which occurs in 19 minutes for regenerators with D/dp = 3, 26 minutes for regenerators with D/dp = 8, and 48 minutes for regenerators with D/dp = 12 The D/dp ratio of the regenerator determines how long it takes for the temperature flow to stabilize after it has reached its steady state. The events leading up to this one take happen in the order listed below: When the heating cycle is in progress, the temperature of the flue gases decreases as they pass through the regenerator bed and into the intake. This is because the particles are absorbing the heat that is being produced by the cycle. This occurs because the particles heat up the flue gases as they pass through the system. On the other hand, as the cooling cycle progresses, the temperature continues to climb. This is due to the fact that the heat that had been stored in the solids is being released into the air that is around them. This results in an increase in the temperature.

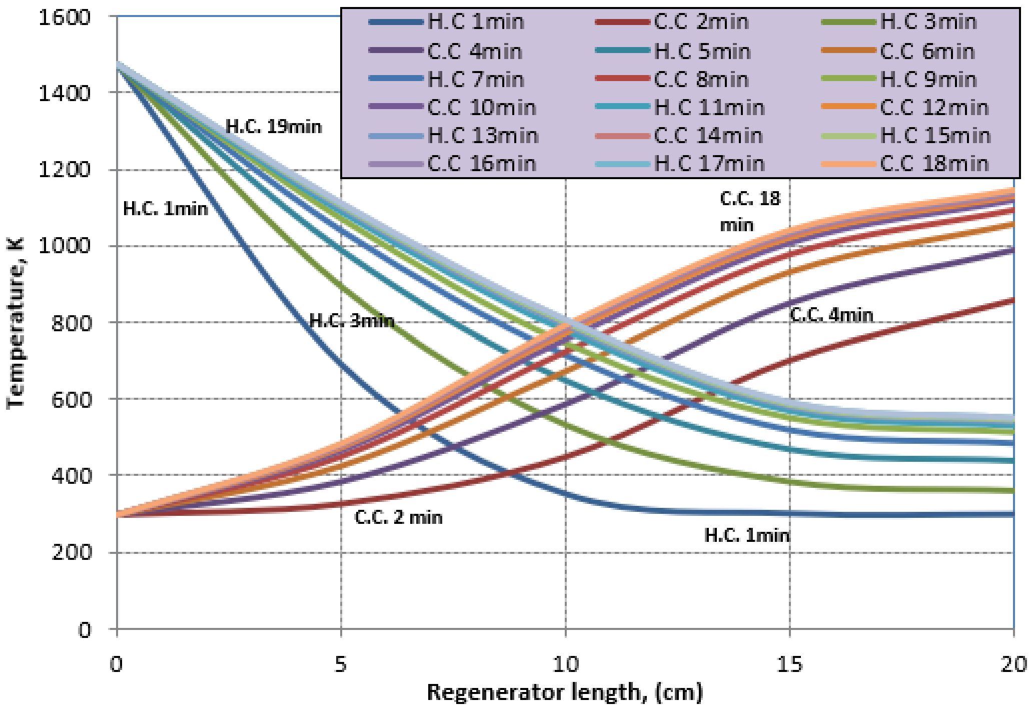

Fig. 8

Variation of temperature along the length of regenerator with H.C. and C.C. after cycle time of 1 min each

According to Figure 8, the steady state of the heat flow is reached at a time equal to 11 minutes. The temperature profile levels out and becomes linear beyond that point; there is no longer a significant difference in temperature after that point. The temperature of the air around us will have climbed to 1144.4 degrees Celsius when the time t equals 18 minutes. It is feasible to determine the temperature efficiency based on the information that has been supplied by using the formula that has been provided and using the information that has been provided.

$n=(T_{a,o}-T_{a,i}) = (T_{g,i}- T_{a,i})$ 10

where Ta,i is the temperature of the ambient air at the inlet (300 K), Ta,o is the temperature of the air at the outlet (1144.4 K), and Tg,i is the temperature of the flue gas at the inlet (1473 K), which equals 72 percent. Ta,o is the temperature of the air at the outlet. The temperature of the air at the outflow is denoted by the symbol Ta,o. The letter Ta,o represents the temperature of the air at the point where it exits the system. The temperature of the air as it leaves the system is represented by the letter Ta,o, which is written in degrees

Celsius.

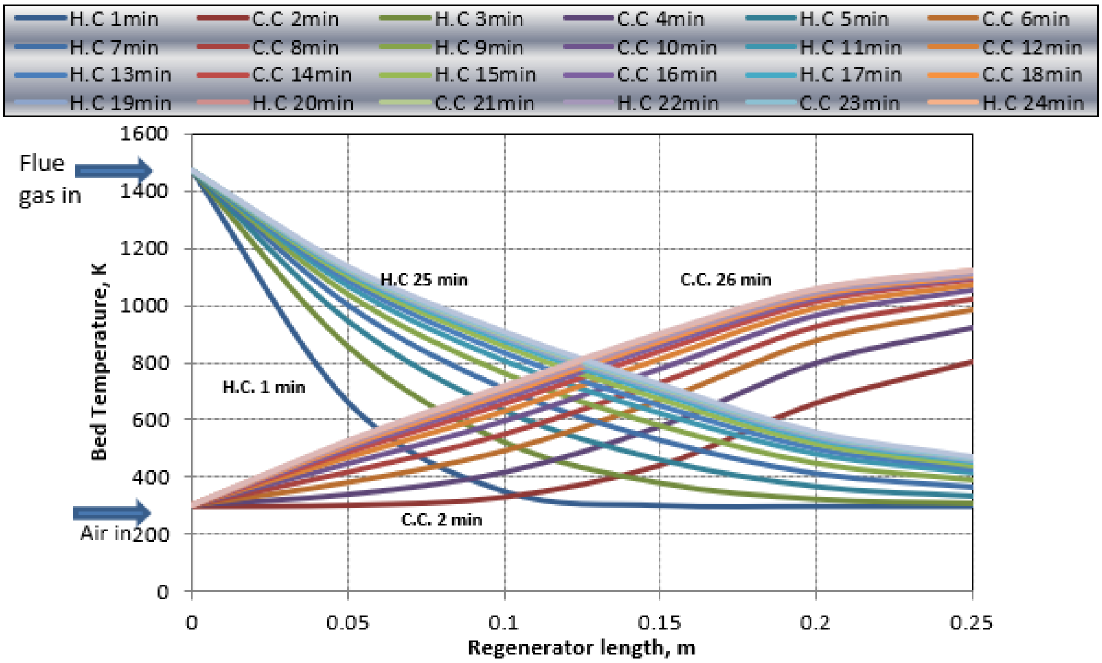

Fig. 9

Variation of temperature along the length of regenerator with H.C. and C.C. after cycle time of 1 min each

Likewise for D/dp=8 Figure 9 illustrates a temperature profile that is linear at the time t=14 minutes has passed. This profile does not have any abrupt gradients, and the heat flow continues to be the same during the whole experiment. Using equation 10, it is possible to estimate the efficiency, and when the temperature of the ambient air is raised up to 1120.2 K at a time t=26 minutes, the efficiency is found to be 70 percent. This is the case when it is determined that it is practical to determine the efficiency. When the temperature of the air is raised to 1120.2 Kelvin, this occurrence takes place.

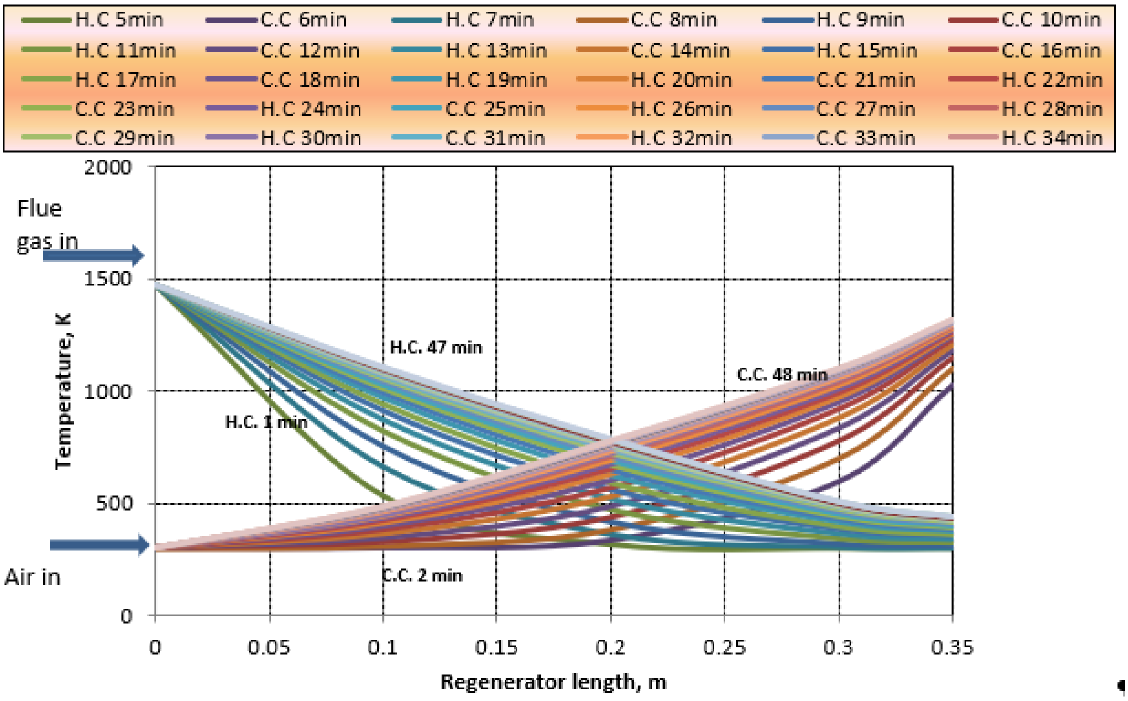

Fig. 10

Variation of temperature along the length of regenerator with H.C. and C.C. after cycle time of 1 min each

At the time point t=17 minutes, the temperature profile depicted in Figure 10 is linear, does not have any steep gradients, and demonstrates steady-state thermal flow with a value of D/dp equal to 12. When the temperature of the air surrounding it is elevated to 1316.9 K, the efficiency is at 86 percent after t=48 minutes, which is when it was measured.

CONCLUSIONS

When the D/dp15 ratio of a fixed-bed regenerator is lower than it should be, the porosity of the interior of the regenerator is said to have an uneven distribution. This occurs when the D/dp15 ratio of the regenerator is lower than it should be. As a direct result of this element, it becomes increasingly difficult to find effective solutions to the problems that are brought on by the flow in these beds. The problems are caused by the flow in these beds. Fluent was used to construct and solve the computational model in order to carry out the research of the fluid flow temperature distribution that occurs inside of the regenerator. This research was carried out in order to better understand how the regenerator works. This investigation was carried out so that we may have a better understanding of the manner in which the temperature is dispersed. It was essential to carry out this analysis so that we could determine how to enhance the regeneration process and make it more effective. The results of the earlier tests were analyzed, and then compared to the thermal and resistance qualities that were supposed to be possessed by the material. The results obtained in the creeping and transition flow regimes were comparable as a result of the high velocities that were discovered in the regions that were located between the solid particles and the unstructured hexahedral meshing that was discovered in these areas. This was due to the fact that the high velocities were discovered in the regions that were located between the solid particles and the unstructured hexahedral meshing that was discovered. This was the case because both of these flow regimes were characterized by a flow that was not steady. This was the reason why this was the case. The regimes of turbulent flow had the largest variance, which reached a maximum of ten percent at its highest point. This percentage was attained at the highest point. Fluent was ultimately employed as the means by which the transient CFD model of the regenerator's modeling was completed and its solution obtained. This model made use of D/dp 3, 8, and 12 in addition to a number of other numbers. Following the completion of the study of the simulated data for each time cycle, an assessment of the efficiency of each regenerator was then carried out (heating and cooling cycle). The transient model of this thermal regenerator has the potential to be effectively used in a broad variety of applications, one of which is Regenerative heat sources. This achievement is included in the body of work that is being presented within the context of this debate, and the thermal and resistance tests on regenerators with a lower D/dp ratio have been accomplished. The projected CFD correlation may be used successfully to build a regenerator with a D/dp ratio of less than 15, and it can be used for all flow regimes, in contrast to Ergun's correlation, which can be used for regenerators with D/dp ratios of more than 15 and for the creeping flow regimes. Ergun's correlation, on the other hand, may be applied to regenerators with D/dp ratios greater than 15 and to the creeping flow regimes. In contrast, the creeping flow regimes and regenerators with D/dp ratios greater than 15 are amenable to Ergun's correlation. In each of these flow regimes, it may be used. In contrast, for regenerators with D/dp ratios greater than 15 and for creeping flow regimes, Ergun's correlation may be applied. This is due to the fact that it considers the creeping flow. Both of these flow regimes will be explained in more detail in the following sentences. On the other hand, the creeping flow regimes and regenerators with D/dp ratios less than 15 may be treated according to Ergun's correlation. This is due to the fact that Ergun's correlation accounts for the creeping flow. This is due to the fact that it considers the flow over a longer time frame.

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