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UNSTEADY FORCED CONVECTION IN PACKED BEDS (COMPUTATIONAL AND EXPERIMENTAL ANALYSIS)

Ricardo Mejía, M.Sc.
Lecturer
Department of Mechanical Engineering
Universidad de Antioquia
M.Sc. Student. University of Illinois at Urbana – Champaign
104 South Wright Street. 216 Talbot Laboratory. Urbana, IL. 61801. USA
rmejiaa2@uiuc.edu

John R. Agudelo, Ph.D.
Professor
Department of Mechanical Engineering
Universidad de Antioquia
Cl. 67 # 53-108 Medellin – Colombia – South America
jragude@udea.edu.co

César Nieto
Graduate Research Assistant
Department of Mechanical Engineering
Universidad Nacional de Colombia
Crr. 64 Cl. 65. Medellin – Colombia – South America
cnieto@unalmed.edu.co

Laura C. Villa
Graduate Research Assistant
Department of Mechanical Engineering
Universidad Nacional de Colombia
Crr. 64 Cl. 65. Medellin – Colombia – South America
lcvilla@udea.edu.co

ABSTRACT

In this work, a process of unsteady forced convection in a packed bed of spheres was experimentally and computationally analyzed.

A device was designed and constructed in order to run the experiments in packed beds. It was used to carry out an experimental run in a packing of ten aluminum spheres, which tube-to-particle diameter ratio was 2,4. Methane-air combustion products were kept flowing into the packed bed at constant inlet conditions, 2,8 m/s and 369ºC. Packed spheres were heated from 25ºC to gases temperature. While heating, temperature of spheres, tube wall and gases at different positions were measured to follow unsteady process.

On the other hand, computational simulation was carried out by modeling the ten-spheres packing under the same flow conditions of the experimental run. Physical properties of gases were kept constant and fluid flow profile was solved before heating process. Results of unsteady temperature variation in different positions showed good agreement with the experimental measures. This result allowed inferring that flow field calculations were a satisfactory representation of the actual flow field, since temperature field variation depends strongly upon flow field.

In conclusion, it was found that the Computational Fluid Dynamics (CFD) simulation is an accurate tool to analyze unsteady forced convection in packed beds. The device designed is a flexible and powerful tool to measure unsteady forced convection in packed beds. The behavior of the gas-to-solid heat transfer coefficient is a fundamental question to solve, and CFD supported on experimental measures is the way to solve it.

INTRODUCTION

Computational Fluid Dynamics (CFD) is a tool that allows studying gases flow inside thermal regenerators by numerical solution of continuity, momentum and energy equations. There is still a slight lack of comprehension of heat transfer and fluid flow features in previous models of packed beds, specifically those related to unsteady convection.

CFD is an alternative method to determine thermodynamic variables behavior in packed bed thermal regenerators. For instance, it allows determining the effect of packed geometry and gases inflow conditions upon packed bed regenerators operation.

A number of previous works such as [1]-[6] have shown CFD potential on studying heat transfer and fluid flow in packed beds. However, those works are limited to steady proceses. Besides, there are works as [7]-[16], that deal with non-thermal equilibrium models of heat transfer in packed beds. Nevertheless, those models do not deal with actual geometry but with a pseudohomogeneous geometry.

In this work, an advance in the field of unsteady forced convection in packed beds is presented. This study applies experimental and computational models to assess thermal behavior of a regenerator under realistic operational conditions.

NOMENCLATURE

a,b,c	Fitting constants
d	Sphere diameter
k_f	Fluid thermal conductivity
Nu	Nusselt number at sphere boundary wall
p_{atm}	Atmospheric pressure [Pa]
q	Heat flux [W/m^2]
T	Temperature [K]

NOMENCLATURE (Cont.)

t	Time [s]
T_∞	Reference temperature [K]

***Experimental Setup*.** Figure 1 shows a picture of the setup built by our group to measure unsteady forced convection in packed beds [17]. Its main duty is to control inlet flow conditions and measure temperature and pressure inside a packed bed thermal regenerator. This characteristic makes possible to know unsteady thermal behavior of the packed bed. Besides, the setup is able to work in a reasonably broad range of flow and temperature conditions (30–700ºC and 0–3m^3/min) to explore unsteady forced and even natural convection in packed beds. Additionally, computational and theoretical results would be verified and supported by experimental results. Technical specifications of the setup are listed in Table 1.

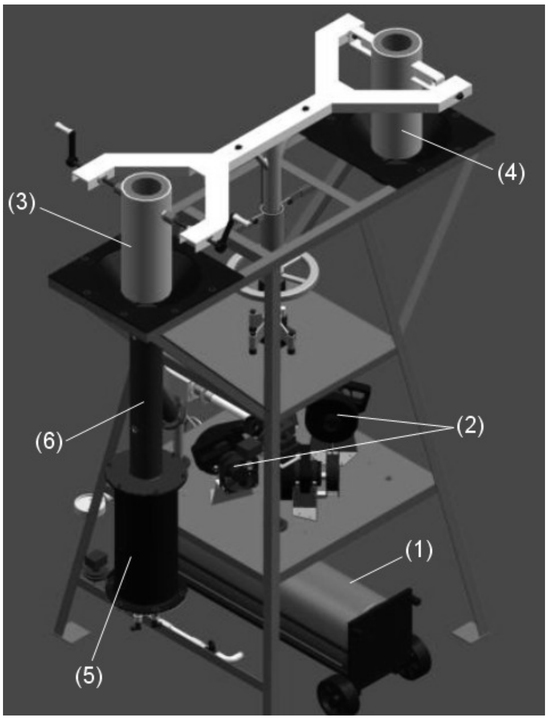

Figure 1. Experimental Setup. The pipe (1) on the bottom is the natural gas source. On the lowest shelf, four blowers (2) are located for combustion system. Two cylinders are located on the two top shelves, the one on the left is for the packed bed (3) and the one on the right is for thermally stabilize (4) the system. They could interchange their positions. The combustion system is located under the left top shelf, composed by a chamber (5) and a duct (6) [17].

Table 1. Technical specifications of the experimental setup

Regenerator diameter	up to 40cm
Regenerator height	up to 50cm
Pressure	up to 3,5Kpa
Volumetric flow	up to 3m^3/min
Combustible	Natural gas
Valve control	Automatic
Combustion control	Automatic
Burner power	5,3KW
Regenerator positioning	Manual

Table 2. (Cont.)

Acquisition channels	96 for temperature 48 for pressure
Combustible source	12,5m^3 x 3000psig pipe
Air source	4 radial fans
Flow meters type	Venturi (0-1psi & 0-5psi)
Thermal isolation	Mineral wool and insulating cement. (surface temperature no greater than 40ºC)

Experimental setting. The experimental process is composed by two stages: 1. System temperature stabilization and 2. Packed bed heating. First stage is to heat the combustion system and ducts before placing the packed bed. This ensures stable inlet temperature once the packed bed is placed to be heated. Second stage begins when the packed bed is placed on the stabilized system to allow combustion gases to flow through it. While flowing, temperatures and pressure are measured to have data of unsteady state.

***Packed bed model*.** Figure 2 shows a model used to make a first approach in studying unsteady forced convection in packed beds. This model was chosen to compare our results with those reported by Logtenberg *et al* [4]. Although they used the same model under steady conditions, their results are a good basis to corroborate physical validity of our study. Moreover, the use of such a relative simple geometry allowed us to reach the necessary knowledge to deal with more complex problems.

Figure 2 shows the packed bed built with ten spheres, which are placed in four horizontal layers. Their positions, relative to a fixed frame, were determined by a CAD program: (0, 0, 0.017); (±0.017, ±0.017, 0.041); (0, ±0.024, 0.069); (±0.024, 0, 0.069); (0, 0, 0.094). Spheres are 0,034m diameter and are packed in a 0,082m diameter tube. The packing is 0,41m height. CFD model avoid contact between spheres and between spheres and the wall by a narrow gap. This gap ensures stability and numerical convergence since a contact point becomes a numerical singularity.

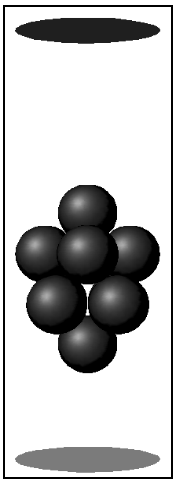

Figure 2. Ten spheres model, used to computationally and experimentally determining thermal behavior of a packed bed under unsteady forced convection.

Simulation settings. Mass conservation, momentum and energy equations, along with their boundary and initial conditions, were solved by the use of Fluent 5. This software brings essential tools for the solution of the governing equation by the application of finite volumes method. This method allows using unstructured grids to model complex domains such as packed beds. Since finite volumes method solution implies exact conservation of mass, momentum and energy inside each control volume, it usually reports smaller errors than other methods.

RESULTS AND DISCUSSION

In the computational model, physical properties were considered independent of temperature, position and time. Logtenberg and Dixon [2]-[3], showed the good agreement of numerical results when the fluid properties are constant during theirs modelations in packed bed reactors. Air was used as fluid phase in CFD runs. Physical properties used for air were as follows:

density = 1.225kg/m^3
thermal conductivity = 0.0242W/m·K
specific heat = 1006.43J/kg·K
viscosity = 1.7894x10^{-5}kg/m·s

Aluminum spheres were used both in CFD and experimental runs. Their physical properties were as follows:

density = 2719kg/m^3
specific heat = 871J/kg·K
thermal conductivity = 202.4W/m·K

In CFD runs, the external wall boundary of the packed bed was considered to be under natural convection. Its heat transfer coefficient was considered to be 10W/m^2·K and its temperature 313.15K. Inlet velocity and temperature were kept the same as in experimental runs. Inlet velocity was 2.7m/s and temperature varied linearly with time as in equation (1).

$$T = 0.0426t + 669.92 \qquad (1)$$

Finally, outlet pressure was considered as local atmospheric pressure in CFD runs, just as in experimental ones, where P_{atm} = 86 kPa.

As initial conditions, we choose zero velocity inside the bed and thermal equilibrium between solid and fluid phases, at room temperature of 300K.

Previously, Mejía *et al* [19] showed that either packed elements, wall or gases temperature can be modeled as a function similar to equation (2) along the unsteady state. *a*, *b* and *c* coefficients must be fitted according to experimental data to relate temperature to time. Equation (2) is then used to fit experimental data and compare with CFD results.

$$T = a + be^{-c \cdot t} \qquad (2)$$

To compare experimental to CFD results, data is plotted in time×temperature graphs. CFD results are plotted in Figure 3. General behavior of temperature shows tendencies similar to those modeled by equation (2), where temperature tends to a value given by coefficient *a* as time tends to infinite. As it was stated by Mejía *et al* [19], coefficient *a* is equal to the inlet temperature; moreover, it is possible to infer from Figure 3 that at least sphere's temperature tends asintotically to equation (1). In addition, Figure 3 shows that sphere's temperature curves are steeper than the wall temperature ones. This is mainly due to two reasons: first, thermal conductivity wall is smaller than spheres one. Then, spheres become thermally saturated faster than the wall. Second, spheres seem to have higher heat transfer coefficients than the wall. Perhaps, this is because the flow is mainly paralell to the wall while it reaches almost all the spheres directly.

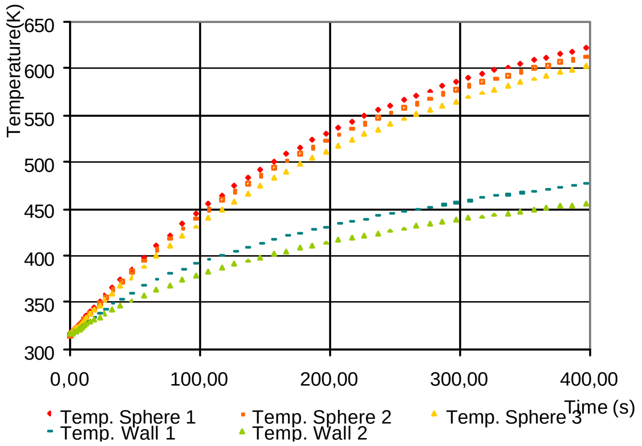

Figure 3. Spheres and wall temperature. Data obtained by CFD.

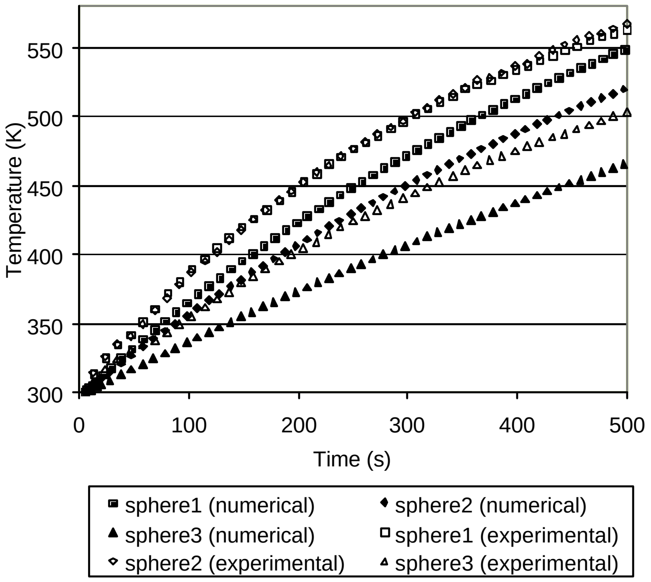

Figure 4. Comparison of CFD and experimental results.

Figure 4 shows the comparison between CFD and experimental results. It shows that both results follow a trend similar to that of equation (2). Although CFD results are steeper than experimental ones, both have the same pattern: first sphere is hotter than the second and that is hotter than the third. It is reasonable because first sphere is the first to be touched by the flow and so on. Accordingly, these are realistic results. Besides, both techniques show that the temperature difference between spheres is small, which is a result of the packed bed array. This model has large voids between packed solids. Then, gases touch them almost uniformly. As a result, they are heated almost homogeneously.

Regarding results, it is possible to see that the difference between methods increases as time passes. Greatest error is reached after 400 seconds and it is about 18%. Regarding that coefficient *c* in equation (2) is directly proportional to heat transfer coefficient *h* [19], a steeper curve is the result of a higher *h*. With this in mind, it is possible to state that the error is caused by the narrow gap between spheres and between spheres and the wall, since this space enhances energy advection near contact points. As a result, CFD model shows a steeper temperature curve than experimental measures. However, the difference between curves decays as time passes and no longer exists beyond 800s. In a previous work, Nieto [20] showed this fact and his results are presented in Figure 5. That curve was obtained under conditions similar to the present work. It shows that the greatest difference between curves is presented about 400s after the beginning of heating process. Curves become indistinguishable beyond 800s. Accordingly, the difference between results in Figure 4 will decay soon and become zero. Then, this is not a catastrophic error.

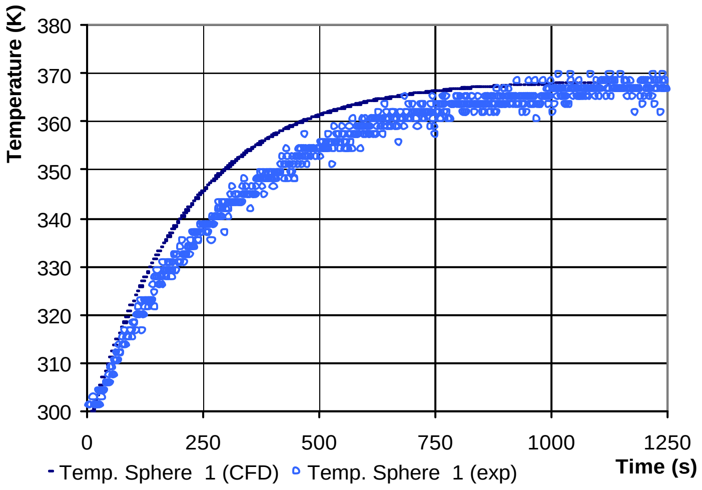

Figure 5. Comparison between CFD model (dotted line) and experimental data (scatter– empty circles) [20].

Despite the differences between numerical and experimental results, it is possible to state that CFD is a valid tool to study unsteady forced convection in packed beds. This statement is supported for previous works in steady forced convection such as [1]-[6].

Computational results allowed us to determine the heat transfer coefficient around spheres by using equation (3).

$$h = \frac{q}{T_{wall} - T_{\infty}} \qquad (3)$$

Where q is the average heat flux and is calculates by Fluent through an overall energy balance at the sphere boundary wall, T_{wall} is the average sphere surface temperature, and T_{∞} is the fluid temperature. *h* was calculated for different times and is used to calculate dimensionless *Nusselt (Nu)* number by using the equation (4) and its variation and results are plotted in Figure 6.

$$Nu = \frac{h \cdot d}{k_f} \qquad (4)$$

That figure shows that *Nu* begins as 77.16 and decay until a constant value where packed bed reaches steady state. This result is in accordance with [26], who showed that the constant value depends upon Peclet number *Pe*. This behavior is due to the fact that the temperature difference between solids and fluid becomes smaller as the time passes.

Table 2 lists the results of average heat transfer coefficient calculated by two known correlations for gas-solid heat exchange in spheres and the average value of Figure 6. Similarity between those results shows coherence in our study.

Table 2. Comparison between average *h* calculated by two correlations and average *h* from our results.

Velocity	2.79 m/s
Reynolds number	6488
Ranz-Marshall correlation for Nusselt number	45.09 W/m^{2}K
Whitaker correlation for Nusselt number	45.45 W/m^{2}K
Average value of *h* (from Figure 6)	48.14 W/m^{2}K

Regarding Figure 6, it is clear that *Nu* and *h* are strongly time-dependent as was showed by Mejía [22]. Consequently, it is particularly important to take in to account this fact when designing thermal regenerators since it is strongly influential upon thermal efficiency. In previous works heat transfer coefficient has been considered as constant as in [23] and [24] or calculated from empirical correlations as in [25]. In the last case, transient behavior has been simulated by taking physical properties as temperature dependent. A more detailed study of heat transfer coefficient will allow to significantly improve up-to-date results. This will be the subject of future work.

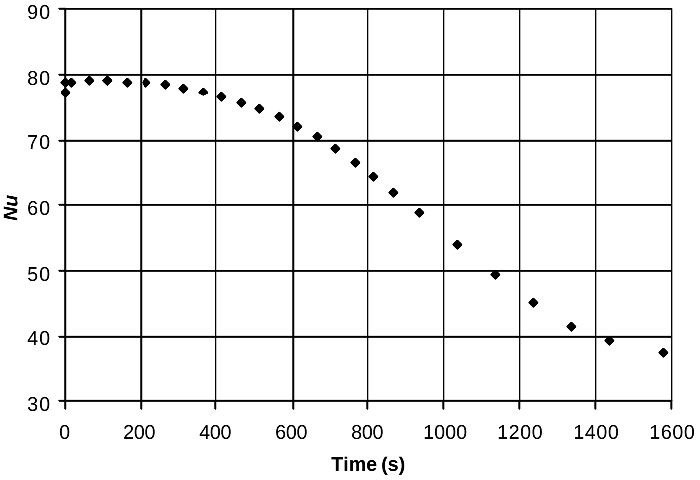

Figure 6. Nusselt number behavior.

CONCLUSIONS

The present CFD model and its experimental verification, allow us to extend Derkx and Dixon [1] conclusion about validity of CFD modeling to study packed beds. They validate the technique for steady forced convection processes, we validate it for unsteady forced convection.

Once this technique was refined to minimize differences between CFD model and experimental results, it will become a tool to design and optimize thermal regenerators.

Heat transfer coefficient in unsteady forced convection strongly time dependent. With this in mind, its study will allow to improve design techniques in thermal regenerators.

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