العنوان:	THE STUDY OF FLUID FLOW BEHAVIOR AND PERFORMANCE PARAMETERS OF A DIFFUSER FILLED WITH POROUS MEDIA OF HIGH PERMEABILITY
المؤلف الرئيسي:	حداد، أحمد نورالدين أحمد
مؤلفين آخرين:	الدوس، طه(مشرف)
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The Study of Fluid Flow Behavior and Performance Parameters of a Diffuser Filled with Porous Media of High Permeability

By

Ahmad Noureldin Ahmad HADDAD

supervisor: Prof. Taha Aldoss

Abstract

Although, wide-angle diffusers are short and compact they have a low-pressure recovery due to the large boundary layer separation at walls and the flow at the diffuser exit is highly non-uniform.

The technique proposed in this work is to introduce porous inserts into diffuser body to play the role of flow straighteners, and redistribute the inlet flow into diffuser domain and energize the boundary layer by fluid of high momentum. This effect is shown to be very useful in reducing the recirculating flow region formed at diffuser walls and decreases pressure losses.

The two dimensional flow into the diffuser partially filled with porous media have been studied numerically using stream function-vorticity model, and coordinate transformation was used to map the physical domain into rectangular domain. The results for clear domain were verified to similar case in literature and the results were found to be in good agreement. Then numerical experiments were conducted with porous inserts at different locations in diffuser domain, and the best location that maximizes pressure recovery was found to be the core region. After that a set of charts were plotted to verify the optimum area and permeability for porous media in order to obtain the maximum pressure recovery at different flow conditions. Energy equation was also solved and a substantial improvement in heat transfer rate due to porous inserts is achieved.

The technique is shown to be very successful, for short wide-angle diffusers, especially as Reynolds number increases.

Key words: Diffuser, Partially filled, Porous media.

دراسة سلوك مائع ومعاملات الأداء لناشر مملوء بمادة مساميّة عالية السماحيّة

إعداد: أحمد نور الدين أحمد حدّاد

إشراف : أ. د. طه الدوس

الملخص :

في هذا البحث تمت دراسة جريان مائع خلال ناشر يحوي على مادة مساميّة عالية السماحيّة. إن وجود المادّة المسامية في جسم الناشر سيؤدي لاعادة توزيع المائع الداخل للناشر مما يؤثر على نموذج الجريان في الطبقة الحدّية المتشكلة على جدران الناشر وبالتالي على أداء الناشر . وقد تمت دراسة جريان المائع خلال الناشر على فرض جريان صفحي ثنائي البعد غير قابل للانضغاط بحل معادلات الاستمرار و كمية الحركة بطرق الحل العددية باستخدام الحاسب الآلي. هذه الطريقة أثبتت فعاليتها خاصة في النواشر القصيرة و الواسعة.

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A_{rp}	Ratio of porous media at exit to inlet area
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C_{pr}	Pressure recovery coefficient
Da	Darcy number , $\frac{K}{H^2}$.
H	Channel half width , m .
K	Porous media permeability , m^2 .
k_e	Thermal conductivity of fluid , $W/m.K$.
k_{eff}	Effective conductivity of the fluid-saturated porous media.
L	Channel length , m .
Nu	Nusselt number , $\frac{Hh}{k_e}$.
p	Pressure , Pa .
Pr	Prandtl number , $\frac{\mu}{C_p k_e}$.
Re	Reynolds number , $\frac{\rho_f u_0 H}{\mu}$.
t	Time , second.
T_b	Bulk region temperature , K .
T_W	Wall temperature , K .
u	Axial velocity , m/s .
U	Contra variant axial velocity , m/s .
u_0	Averaged velocity at inlet , m/s .
v	Vertical component of velocity m/s
V	Contra variant vertical velocity , m/s .
x	Axial coordinate.
y	Transverse coordinate.

Greek symbols

α_e	Thermal diffusivity of fluid , m^2/s .
α_{eff}	Effective diffusivity , m^2/s .
β	Aspect ratio

ϕ	Porosity
η	Transverse coordinate in physical domain.
μ	Dynamic viscosity of fluid $Kg\ m^{-1}s^{-1}$
$\tilde{\mu}$	Effective viscosity $Kg\ m^{-1}s^{-1}$
θ	Nondimensional temperature
ρ_f	Density of fluid $Kg\ m^{-3}$
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τ_W	Shear stress at wall N/m^2s
ω	Vorticity component in 2-D problem
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JORDAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

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By

Ahmad Noureldin Ahmad Haddad

Thesis Submitted in Partial Fulfillment of the Requirements of the Degree
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Chapter One

Introduction and Literature Review

1-1 Introduction

A diffuser is an important component in several fluid systems, which is often used to slow down the flow by converting its kinetic energy into pressure rise. Examples are aircraft engine intakes, the exhaust diffuser for a gas turbine, piping system, wind tunnels, and combustors.

In all applications maximum recovery of static pressure should be achieved to obtain good performance. Conventional diffuser has the most uniform velocity profile however; this is limited to small-included angles. Small-angle diffusers need to be long to achieve the required area change. This adds to cost and space.

Short wide-angle diffusers are compact and less costly, but suffering from boundary layer separation, which leads to a reduced performance. In addition to reduction in performance, wide-angle diffusers have highly nonuniform velocity profiles.

The performance of diffusers affects strongly the conditions at which subsequent components operate. Hence, the well-designed diffuser should produce not only maximum pressure recovery but also minimum level of distortion, unsteadiness, and velocity nonuniformty at exit plane. For example, Combustion chamber in case of aircraft engines depends critically on diffuser performance, also the turbine engine inlet diffuser which slow down the air delivered to the inlet of compressor must not exhibit more than a minimum level of distortion to assure good compressor performance.

A number of methods have been adopted to keep diffusers short and at the same time to achieve high performance, such as using vaned diffuser, wall suction/injection, passive boundary layer control, vortex generator at inner walls or introduction of swirl at the inlet.

These methods are primarily based on transferring kinetic energy into the regions of low energy to energize the boundary layer with fluid of high momentum.

1-2 Literature review

Much of work on diffusers comes from the period from the 1950s through the 1980s. In this period of time, a considerable amount of research was done in the experimental laboratory to cover some of performance characteristics of diffusers of a variety of inlet conditions and different cross sections.

For a vaneless diffuser which is the simplest diffuser, a collection of papers by [1, and 2]; allow the designer to estimate pressure recovery in simple methods. The systematic studies of two-dimensional straight walled diffusers of variable diverging angels carried out by [3] in the latest 1950 led to classification of the flow region behavior according to the characteristics of the stalled flow pattern.

A number of techniques were adopted to improve the efficiency of simple diffuser like using splitters and vanes. They divide the diffuser into a number of smaller diffusers to reduce and separate the effects of stall (local separation of the boundary layer), [4]. This technique used in diffuser system of a centrifugal compressor and proved higher efficiency but narrow operating range, [5]. This technique have used by [6], in practical electrostatic precipitator where, he used wide-angel diffuser with one or more perforated perpendicular plates to flow direction to save space and to help having a uniform velocity distribution at the exit plane. This arrangement was found to have the efficient removal of dust particles from polluted air.

In laminar flow conventional diffusers, there is no sufficient mixing occurred between the bulk flow and the boundary layer which, lead to flow separation downstream. A satisfactory solution, by [7] proved to be the injection of high-velocity air along the wall from a narrow annulus around the inlet. The technique of injecting a high-velocity annular wall jet to energize the boundary layer had been successful at higher Reynolds numbers, [8]. However in many cases energizing the boundary layer at the inlet by swirl or turbulence would still have led to separation but delaying boundary layer separation point.

Energizing the boundary layer over the whole diffusing section either by suction or injection provides the best performance gains, [9]. Tripping the boundary layer on the inner wall a distance away of diffuser inlet although, associated with losses, the onset of stall in the diffuser can be postponed.

The passive boundary layer control with a combination of suction and blowing which is originally developed for drag reduction can be used to improve diffuser performance. It can produce a modest rise in pressure recovery and significant reduction in flow unsteadiness. The concept of passive boundary layer control is based on simultaneous suction and blowing by linking low-pressure region and high-pressure region by porous surfaces made of holes and slots. Natural pressure rise in the direction of the flow in diffuser was used to reduce the thickening of boundary layer downstream, [10].

Another technique is to add a ring shaped flap or more around the diffuser exit [11], such an arrangement creates a narrow gap between the flap and the diffuser, which accelerates part of outer air and directs it into the diffuser wake flow. The result was a reduction in the diffuser outlet pressure and an increase in mass flow and air speed. This technique and others were investigated numerically using ready finite element package by [12].

1-3 Research Objectives

The aim of this work is to study the impact of introducing porous medium of high permeability into the diffuser on the short wide-angle diffuser performance in terms of the following aspects:

- The uniformity of velocity profile at exit plane.
- The pressure recovery performance.
- The size and location of separation region.

Laminar flow, symmetric, two-dimensional diffusers of high expansion ratio will be studied using numerical methods. Attention will be focused on low Reynolds number. The optimum size and location of the porous media that lead to best performance are determined and the region of recirculating flow and separation point will be evaluated and compared to diffusers of the same geometry with clear domain to see the advantages and shortcomings of such diffusers.

Chapter Two

Mathematical Model

2-1 Flow Geometry

The problem under investigation consists of two-dimensional channel with gradual expansion from inlet to outlet. This geometry is similar to that proposed by [13]. The main flow is in x-direction. The inlet and exit planes are considered to be perpendicular to x-axis as shown in fig. (1).

All dimensions are normalized by H (half channel width). Half-domain was used for calculations assuming flow symmetry about the centerline of the channel. The assumption of symmetry flow is justified at low Reynolds number.

2-2 Mathematical Formulation

In this work a diffuser partially filled with porous is considered.

The governing equations for two-dimensional incompressible, laminar viscous flow, and clear domain assuming constant properties, homogeneous, and Newtonian fluid are:

$$\vec{\nabla}.\vec{v} = 0$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v}.\vec{\nabla})\vec{v} = \frac{-1}{\rho}\vec{\nabla}.p + \frac{\mu}{\rho}\nabla^2 \vec{v} \qquad (1)$$

The continuity equation holds true for porous media domain by identifying $\vec{v}$ to be volume-averaged velocity. However, for momentum equation Darcy's law with Brinkman and Forchheimer extensions should be considered. Furthermore, by analogy with the Navier-Stokes equation, convective terms are also added to the porous media equations to maintain consistency with clear fluid flow [14]:

$$\frac{1}{\phi}\frac{\partial \vec{v}}{\partial t}+\frac{1}{\phi^{2}}(\vec{v}.\vec{\nabla})\vec{v}=\frac{-1}{\rho_{f}}\vec{\nabla}.p+\frac{\tilde{\mu}}{\rho_{f}.\phi}\nabla^{2}\vec{v}-(\frac{\mu}{\rho_{f}.K}+\frac{C}{\sqrt{K}}|\vec{v}|)\vec{v} \qquad (2)$$

Although we analyze steady state problem the time derivative is included since the final mathematical model is solved using time-marching procedure that is described later in chapter 3.

The two sets of equations (1) and (2) are coupled by the matching conditions at the fluid /porous-layer interface. These conditions express continuity of normal and tangential velocities, normal and shear stresses, pressure, and temperature. For partially filled porous channel, instead of solving the two sets of equations separately, the equations can be combined into one set. This is valid when porosity is close to unity [15]. Using this one equation model (2) the matching conditions at the fluid/porous-layer interface are considered to be automatically satisfied. This simplifies the numerical solution by a great deal. The inclusion of Brinkman's extension and the convective terms in the porous media equation eliminates the need for imposing an explicit interface condition, since these terms also guarantee continuity and interfacial shear stress [16].

The two dimensional problem is formulated in terms of vorticity-stream function model, which can be written as follows,

$$\frac{1}{\phi}\frac{\partial \omega}{\partial t}+\frac{1}{\phi^2}\left[\frac{\partial(u.\omega)}{\partial x}+\frac{\partial(v.\omega)}{\partial y}\right]=\frac{\tilde{\mu}}{\rho_f.\phi}\nabla^2\omega-\left(\frac{\mu}{\rho_f K}+\frac{C}{\sqrt{K}}|\bar{v}|\right)\omega \tag{3}$$

$$\omega=\frac{\partial v}{\partial x}-\frac{\partial u}{\partial y} \tag{4}$$

Here vorticity vector is normal to the plane, and has only one component ω. This equation is called vorticity transport equation.

By the definition of stream function for two-dimensional problems continuity equation is satisfied automatically by velocity relations,

$$u=\frac{\partial \psi}{\partial y} \quad , \qquad -v=\frac{\partial \psi}{\partial x} \tag{5}$$

Elliptic Poisson equation for stream function is obtained By substituting equations (5) into equation (4)

$$-\omega=\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^2\psi}{\partial y^2}=\nabla^2\psi \tag{6}$$

The equation (4) and (6) are two coupled equations, and can be solved using equation (5) to obtain velocity field.

An additional equation for pressure field can be derived, by taking the divergence of equation (2):

$$\nabla^2 p=\frac{2\rho}{\phi^2}\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y}-\frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right)=\frac{2\rho}{\phi^2}\left[\frac{\partial^2\psi}{\partial x^2}\frac{\partial^2\psi}{\partial y^2}-\left(\frac{\partial^2\psi}{\partial x\,\partial y}\right)^2\right] \tag{7}$$

The presence of porous media gives additional surface area and improves fluid mixing, which gives arise to the overall heat transfer.

The extreme importance of this subject in real world application has motivated the study of thermal field.

Energy equation for laminar forced convection under assumption of local thermal equilibrium of fluid and solid matrix is written as:

$$\sigma \frac{\partial T}{\partial t} + \frac{\partial (uT)}{\partial x} + \frac{\partial (vT)}{\partial y} = \frac{k_{eff}}{\rho_f \, Cp} \nabla^2 T \tag{8}$$

Where σ is the thermal capacity ratio, defined as follows

$$\sigma = \frac{\phi \rho_f C_{pf} - (1-\phi) \rho_f C_s}{\rho_f C_{pf}}$$

And k_{eff} the effective thermal conductivity

$$k_{eff} = \phi \, k_e + (1-\phi) \, k_s$$

The boundary conditions for the previous equations will be discussed in the next section. Now using H, u_0, $T_w - T_b$, $\rho_f \, u_0^2$ as the scales for length, velocity, temperature, pressure, respectively. Equations (3), (6), (7), (8) in nondimentional form are written as:

$$\frac{\partial \omega}{\partial t} + \frac{\partial (u.\omega)}{\partial x} + \frac{\partial (v.\omega)}{\partial y} = \frac{\phi \, \tilde{\mu}/\mu}{\mathrm{Re}} \nabla^2 \omega - [\frac{1}{\mathrm{Re}\, Da} + \frac{C}{\sqrt{Da}} |\vec{v}|]\phi^2 \, \omega \tag{9}$$

$$-\omega = \frac{\partial_2 \psi}{\partial x^2} + \frac{\partial_2 \psi}{\partial y^2} \tag{10}$$

$$u = \frac{\partial \psi}{\partial y} \quad , \qquad -v = \frac{\partial \psi}{\partial x} \tag{11}$$

$$\nabla^2 p = \frac{2}{\phi^2}\left(\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right) = \frac{2}{\phi^2}\left[\frac{\partial_2 \psi}{\partial x^2}\frac{\partial_2 \psi}{\partial y^2} - \left(\frac{\partial_2 \psi}{\partial x\,\partial y}\right)^2\right] \tag{12}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial (u\theta)}{\partial x} + \frac{\partial (v\theta)}{\partial y} = \mathrm{Re}^{-1}\,\mathrm{Pr}^{-1}\,\frac{k_{eff}}{k_e}\nabla^2\theta \tag{13}$$

$$\theta = \frac{T - T_b}{T_W - T_b}, \quad p = \frac{\overline{p} - p_0}{\rho_f u_0^2}$$

Where

$\mathrm{Re} = \frac{\rho_f u_0 H}{\mu}$ Reynolds number

$\mathrm{Pr} = \frac{\mu}{C_p k_e}$ Prandtl number

The reference time was chosen to have unity coefficient of transient term, this would not make confusion since the stable solution after decaying of transient term would be the final solution.

The friction factor can be found by applying the nondimensional parameters on the shear stress at the wall.

$$C_f = \frac{\tau_W}{\rho_f\, u_0^2/2} = \frac{\frac{\tilde{\mu}}{\phi}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)}{\rho_f u_0^2/2} = \frac{2\,\mathrm{Re}^{-1}}{\phi}\frac{\tilde{\mu}}{\mu}\left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)\Bigg|_w \tag{14}$$

The heat transfer coefficient and Nusselt number are

$$q_w = -k_{eff}\,\Big(\sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2}\,\Bigg|_w = h(T_m - T_w)$$

Where T_m the mixing cup temperature

In nondimensional form, Nu becomes:

$$Nu = \frac{H\,h}{k_e} = \frac{K_{eff}/K_e}{\theta_w - \theta_m}\left(\sqrt{(\frac{\partial\theta}{\partial x})^2 + (\frac{\partial\theta}{\partial y})^2}\right)\Bigg|_w \tag{15}$$

2-4 Generalized Coordinate System - Physical Domain

The mathematical model for nonrectangular flow region is presented using generalized coordinate system with the new independent variables $\xi = f(x,y), and\ \eta = f(x,y)$. The Cartesian velocity components u, and v are replaced by contra variant velocity components U, and V as new dependent variables and defined as:

$$\begin{aligned} U &= u\,y_\eta - v\,x_\eta \\ V &= -u\,y_\xi + v\,x_\xi \end{aligned} \tag{16}$$

Analytically, these relations may be inverted to obtain:

$$\begin{aligned} u &= U\frac{x_\xi}{J} + V\frac{x_\eta}{J} \\ v &= U\frac{y_\xi}{J} + V\frac{y_\eta}{J} \end{aligned} \tag{17}$$

Where: $J = x_\xi y_\eta - x_\eta y_\xi$

Scalar variables like stream function, temperature, and pressure are invariant under coordinate transformation. The equations (9, 10, 12, and 13) are written in terms of $\xi, and\ \eta$ as follows.

- Vorticity transport equation

$$\frac{\partial\omega}{\partial t} + \frac{1}{J}\frac{\partial(U\omega)}{\partial\xi} + \frac{1}{J}\frac{\partial(V\omega)}{\partial\eta} = \frac{\mathrm{Re}^{-1}\phi}{J}\Big[\frac{\partial}{\partial\xi}\big(\frac{q_{11}}{J}\omega_\xi + \frac{q_{12}}{J}\omega_\eta\big) + \frac{\partial}{\partial\eta}\big(\frac{q_{21}}{J}\omega_\xi + \frac{q_{22}}{J}\omega_\eta\big)\Big] - \big((Da\,\mathrm{Re})^{-1} + \frac{C}{\sqrt{Da}}|\vec{v}|\big)\phi^2\,\omega \tag{18}$$

- Stream function equation

$$-\omega = \frac{1}{J}\frac{\partial}{\partial \xi}\left(\frac{q_{11}}{J}\psi_\xi + \frac{q_{12}}{J}\psi_\eta\right) + \frac{1}{J}\frac{\partial}{\partial \eta}\left(\frac{q_{21}}{J}\psi_\xi + \frac{q_{22}}{J}\psi_\eta\right) \tag{19}$$

$$U = \frac{\partial \psi}{\partial \eta} \qquad V = -\frac{\partial \psi}{\partial \xi} \tag{20}$$

- Pressure equation

$$\frac{1}{J}\frac{\partial}{\partial \xi}\left(\frac{q_{11}}{J}p_\xi + \frac{q_{12}}{J}p_\eta\right) + \frac{1}{J}\frac{\partial}{\partial \eta}\left(\frac{q_{21}}{J}p_\xi + \frac{q_{22}}{J}p_\eta\right) = S \tag{21}$$

Where

$$S = \frac{2}{\phi^2 J^2}\left[\frac{\partial u}{\partial x}\frac{\partial v}{\partial y} - \frac{\partial u}{\partial y}\frac{\partial v}{\partial x}\right] \tag{22}$$

- Energy equation

$$\begin{aligned}\frac{\partial \theta}{\partial t} + \frac{\partial (U\theta)}{\partial \xi} + \frac{\partial (V\theta)}{\partial \eta} = \frac{\mathrm{Re}^{-1}\,\mathrm{Pr}^{-1}}{J}&\left[\frac{\partial}{\partial \xi}\left(\frac{q_{11}}{J}\theta_\xi + \frac{q_{12}}{J}\theta_\eta\right)\right.\\ &\left. + \frac{\partial}{\partial \eta}\left(\frac{q_{21}}{J}\theta_\xi + \frac{q_{22}}{J}\theta_\eta\right)\right]\end{aligned} \tag{23}$$

The metrics are defined as

$$\begin{aligned} q_{11} &= x_\eta^2 + y_\eta^2 \\ q_{12} = q_{21} &= -x_\xi x_\eta - y_\xi y_\eta \\ q_{22} &= x_\xi^2 + y_\xi^2 \end{aligned} \tag{24}$$

A schematic view to the physical domain being considered is shown in fig. (2). The lines of constant ξ, η are illustrated. The calculations were made by set $H = 1, L = {}^{10}\!/_{3}$.

2-4 Boundary Conditions

Listed hereinafter the boundary conditions used for solving velocity, pressure, and temperature field. The specification of these boundary conditions is extremely important since they directly affect the stability and accuracy of the solution. Exit boundary condition need special treatment since the down stream portion of the flow domain are open.

- Velocity Field

The equations that govern the flow field are the vorticity transport equation (18), the stream-function-vorticity equation (19), and the stream-function-velocity relation (20). Since ψ ,ω are the primary variables, they must be specified at all boundaries.

At inlet Poiseuille flow for velocity distribution were considered,

$$\left.\begin{aligned} u_0 &= \frac{3}{2}(1-y^2) \\ v_0 &= 0 \end{aligned}\right\} \xrightarrow{eq(16)} U_0 = y_\eta\big|_{\xi=0} u_0 \,, \quad V_0 = -y_\xi\big|_{\xi=0} u_0$$

The vorticity at inlet

$$\omega_0 = -\frac{\partial u}{\partial y} = 3y \quad , \quad y = \eta \;\; y_\eta$$

follows from definition of stream function

$$\psi = \int_0^y u \, dy + f(x) \rightarrow \psi\big|_{x=0} = \frac{1}{2}(3y - y^3)$$

where the arbitrary function $f(x)$ chosen to be zero at lower wall.

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