Numerical Investigations on Fluid Flow through Porous Media and Empirical Correlation for Pressure Drop

Siva Murali Mohan Reddy.A, Venkatesh M. Kulkarni

Abstract: ***This paper presents a numerical investigation on the effect of parameters like bed to particle diameter ratio, shape of the porous material, porosity and particle diameter by which the porous medium has been made on pressure drop. And the direct empirical correlations for the same are established. Core and annulus are the two shapes of porous medium considered for investigation which are more popular in literature. It is observed that all the three parameters show a positive effect i.e reduction in pressure drop when their values are increased. Further investigation shows that there is a critical bed to particle diameter ratio beyond which the effect of shape of the porous medium on pressure drop is negligible***.

Index Terms: ***About four key words or phrases in alphabetical order, separated by commas.***

I. INTRODUCTION

Flow through porous media is already-met in engineering and scientific areas of research. Representative Fields of interest includes soil mechanics, filtration, and evaporation of water from leaves. Correspondingly. Packed beds are widely used in heat transfer devices and catalytic reactors for heat transfer augmentation. Transport process in a packed bed is known by the relationship between the velocity of the fluid and pressure drop. The same relationship can be applied to study fluid flow characteristics through other porous media such as petroleum reservoirs, soil, rocks, aquifer, and filters. Since the pressure drop in packed beds is very important and is directly related to the pumping power, the pressure drop prediction must be done using an accurate correlation. Darcy's law gives the relationship among fluid viscosity, rapid discharge rate through a porous medium and pressure drop

$$\frac{\Delta P}{\Delta X} = \frac{\mu}{k} Vs$$

where ΔP is identified as drop in pressure towards the length ΔX of the medium, , μ is the fluid dynamic viscosity, k indicates permeability of the porous medium and Vs is the shallow fluid velocity. This law can be precisely proven by means of the homogenization explanation, by Sanchez-Palencia and Tartar in 1980.

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Mr. Siva Murali Mohan Reddy.A Assistant Professor Department of Mechanical Engineering at Sapthagiri College of Engineering, Bangalore,

Dr.Venkatesh M.Kulkarni, Professor Department of thermal power engineering VTU Centre for Postgraduate Studies, Gulbarga, Karnataka

After Many years of Darcy's experiments, some researchers identified the deviation in Darcy's law when the seepage velocity value increases beyond certain limit. Reynolds conducted many experiments on nonlinear effects induced by inertia forces in fluid flows through porous media and it has been observed that nonlinear effects starts appearing when the fluid flow velocity increases, keeping the darcys law application limited to low velocity flows or viscous flows. It has been observed that the relevant parameter in Darcy's experiment is the Reynolds number based on seepage velocity. The Pressure drop correlation during uni-dimensional flow through a packed bed by accounting the nonlinear effects is given by Forchheimer equation.

$$\frac{\Delta P}{\Delta X} = \frac{\mu}{k} V + Cf \rho V^2$$

Where Cf indicates the coefficient of inertia and ρ is the density of fluid. Till date, many theoretical and experimental correlations are obtained to find the pressure drop in packed beds. Among these the Ergun equation emerged as most widely used empirically derived model. In this equation the sum of the pressure losses obtained from the inertial and viscous energy loss designated as total pressure drop.

$$\frac{\Delta P}{\Delta X} = E_1 \frac{(1-\epsilon)^2}{\epsilon^3} \quad \frac{\mu v}{Dp^2} + E_2 (\text{-} \frac{(1-\epsilon)}{\epsilon^3} \quad \frac{\rho v 2}{Dp^2}$$

Phillips et al. [2] conducted experiments on fluid flow through different types of sand stones and dimensions which acts like a porous media and proposed empirical correlations based on statistical analysis of large amount of experimental data. These correlations are used to predict compressional and shear velocities for fluid flow in 64 different types of sand stones using only three parameters i.e effective pressure, porosity and clay content. The work of Mouaouia Firdaouss et al. [3] shows that, the nonlinear correction to Darcy's law is quadratic in terms of the Reynolds number for periodic porous media, whose period is of the same order as that of the

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Lage, J.L.et al. [4] predicted the relationship between the mean seepage velocity of fluid and pressure gradient for air flowing through a porous medium using a theoretical semi variance model. Analysis indicates that the pressure difference versus speed of the fluid relation departs from the quadratic Forchheimer-extended Darcy flow model. And it is corrected by correlating a cubic function of fluid speed for the velocity range of their experiments. Liu, J.F.et al.[5] Conducted experiments to obtain pressure drop in seven different types of aluminum foams with different pore densities and various porosities.

For the same, empirical correlations were developed to correlate the dimensionless pressure drop with the dimensionless flow velocity. According to the empirical correlation and the experimental data, it is found that the pressure drop in foam matrixes was much lower than that by granular matrixes for the same Reynolds number.

Wei Zhong et al. [6] Conducted experimental investigation on air flow through porous media made up of. Sintered metal to determine pressure drop characteristics. He found that compressibility and inertial affects also significantly contribute to pressure drop. A modified Forchheimer equation was developed, including, these two parameters which are neglected by Forchheimer. Choi et al. [7] In their work showed that the wall effect depends on the Reynolds number as well as on the bed-to-particle diameter ratio for small bed-to-particle diameter ratios, further obtained correlation for the same.

Experiment to study the velocity–pressure drop relationship for water (Vw–ΔPw) and air (Va–ΔPa) in coarse granular porous materials was undertaken by Rune R et al. [8] The experiments show a strong relationship between the two, this relationship could be described using a single model constant (f). for air flow (f_a) and for water flow (f_w), or their ratio ,facilitate prediction of the Vw–ΔPw relationship from the Va– ΔPa relationship and vice versa in the same porous medium.

Prashant Kumar, Topin [9] in their review paper presented the various pressure drop correlations as well as highlights the uncertainties and deviations in various definitions of several key parameters. Comparison shows that among all the studies of pressure drop correlations presented, inertia coefficients and permeability are very significantly sensitive to the range porosity and are strictly depend on shape.

Sharma et al [10] reviewed various correlations and equations to evaluate beta coefficient and It has been observed that beta coefficient is highly influenced to rock properties like permeability, tortuosity and porosity and. He developed algorithm to obtain the beta coefficient values. It has been observed that calculated beta value predicts pressure gradient change with respect to velocity accurately. Prashant Kumar , Frederic Top [11] in their compressive study made effort to identify bias in various pressure drop data obtained experimentally using various methodologies to extract flow law characteristics. Overall study concludes that the permeability and inertia coefficient are very sensitive to the porosity range and are strictly shape dependent. Most of the studies presented in the above literature were concentrated and developed empirical correlations for pressure drop.

Considering the effects of permeability, tortuosity, porosity etc. Whereas the important parameters like bed to particle diameter ratio, particle diameter and shape of the porous medium were received less concentration. However many applications for fluid flow through porous media involves study of pressure drop against velocity and there is a lack of direct empirical correlations to predict the same.in this context the main objective of the present study is to develop a direct empirical correlations by including the effects of parameters like bed to particle diameter ratio, shape of the porous media, porosity and particle diameter.

II. NUMERICAL SIMULATIONS

The two models considered for analysis are shown in schematic diagram.Fig.1.(a) &(b) The assumptions Treated in numerical analysis includes, an empirically determined value which offers resistance to flow acts like a porous medium. Porosity for the porous media model is accounted in governing equations. In general, the porosity is assumed as isotropic and pressure interpolation scheme is used inside porous media zones .a local thermal equilibrium (LTE) is assumed to be exist between fluid and solid phase. The experimental results S.M. Mohan Reddy *et* al. [1] are used to verify and validate the numerical model been accepted, prepare it in two-column format, including figures and tables.

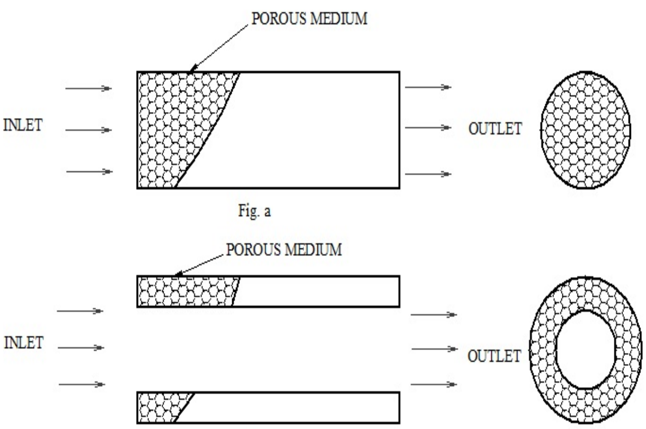

Fig 1: Schematic diagram of porous medium a)core shape b) annular

Numerical simulations are performed using Ansys fluent. Pressure fields are calculated for the entire porous region. Methodically verified mass in-balance and observed that there are no variations in the overall flow. Periodicity is applied in only x direction and Boundaries are set as symmetry planes. The mass flow rate is varied from 0.025 to 1 kg/s for different values of porosities, bed to particle diameter ratio and particle diameter. By doing so, a large number of data points were obtained to get accurate correlations. The fluid medium used is assumed to

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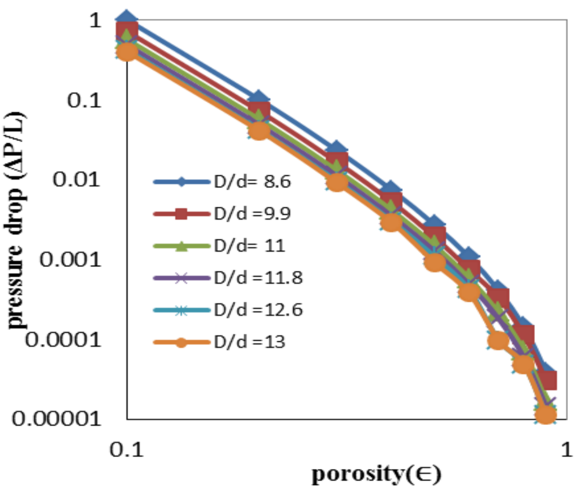
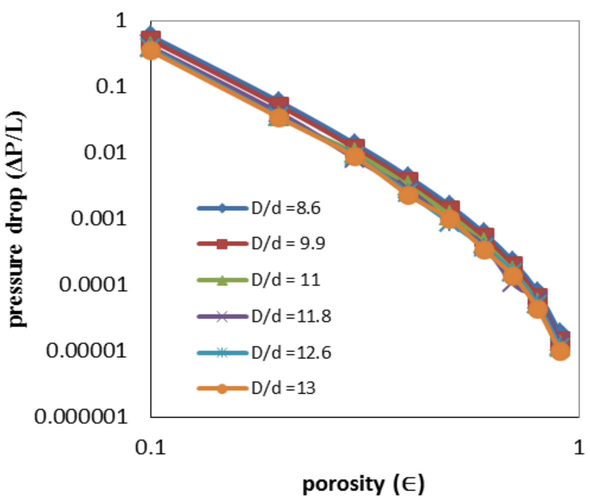
be having constant density of 998 kg /m3. Further numerical analysis is also carried out by varying mass flow rate fluid for different values of core and annular diameters. Porosity values ranging from 0.1to 0.9 were considered.

III. RESULTS AND DISCUSSIONS

The numerical results are presented in fig.2 show the influence of varying the porosity for both core (a) and annulus shape (b) porous medium bed with identical volume on pressure drop, assumed to be made up of uniform 5 mm particle diameter with sphericity of 0.75. For steady mass flow rate of 0.025 kg/s for bed to particle diameter ratio ranging from 8.6 to 13.the plots illustrate that, pressure drop per unit length decreases with increase in bed to particle diameter ratio.



(a)



(b)

Fig 2. Pressure drop against porosity for different values of bed to particle diameter ratio a) core shape bed b) Annulus shape bed

This effect is more dominant for core shape bed then annulus shape. And also it can be seen that at D/d ratio of 13 there is no further decrease of pressure drop value for both the shapes, and the pressure drop lines in a plot coincide with the previous one. Two separate empirical correlations are developed for core and annulus shape which is utilized to find the pressure drop for porosity values ranging from 0.1 to 1 within the range of bed to particle diameter ratio 13. The numerical simulations are repeated by varying the mass flow rate in a step of 0.010 for 6 values and particle diameter for 1mm to 10 mm. Results shows that the difference of pressure drop per unit length against porosity for both core and annulus shape bed porous medium become weakened with the increase of (D/d) ratio and finally the values of pressure drop coinciding for bed to particle diameter ratio ranging from 12.5 to 13. Fig.4(a) Demonstrates the same.

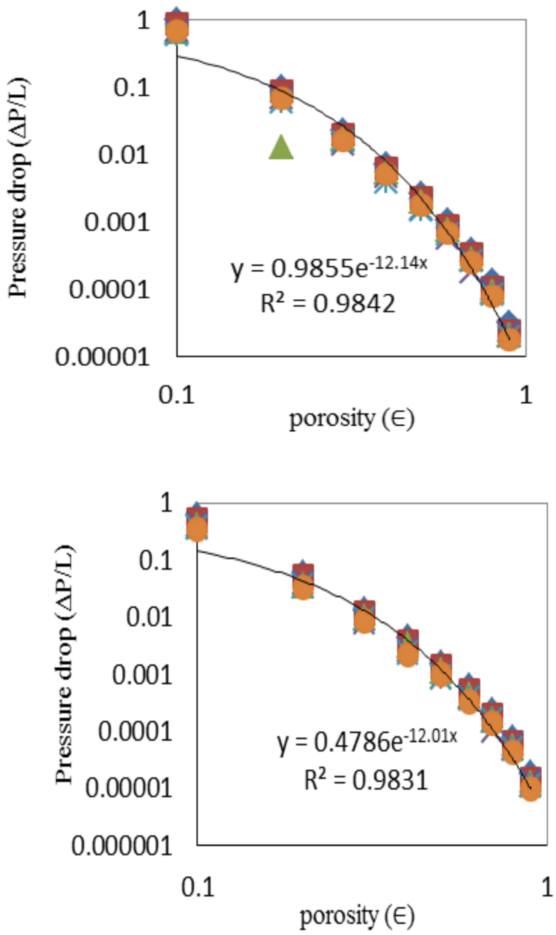


Fig.3 correlations for pressure drop against porosity (a) core shape (b) Annulus shape

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The correlations are obtained by using scattered plots fig.3 (a) and (b) for both the shapes.

Correlation for pressure drop Vs porosity (Core shape porous media) $0.1\leq \in \leq 1$	R^2
1) $\Delta P/L=0.98e^{-12.14\epsilon}$ $D/d \leq 13$	0.984
Correlation pressure drop Vs porosity (Annulus shape shape) $0.1\leq \in \leq 1$	
2) $\Delta P/L = 0.4786e^{-12.01\epsilon}$ $D/d \leq 13$	0.983

This could be attributed to the fact that there exist a critical bed to particle diameter ratio (D/d) above which shape of the porous medium has very negligible effect on pressure drop and also for which the core and annulus shape porous media gives same values of pressure drop.

It gives us the clear picture about maximum diameter of porous medium can be increased for particular particle diameter which nullify the effect of shape of porous media. Based on this scenario one can conclude that same correlation can be used to find the pressure drop values against porosity for both the shapes. And fig.4(b) shows the correlation obtained by using scattered plot.

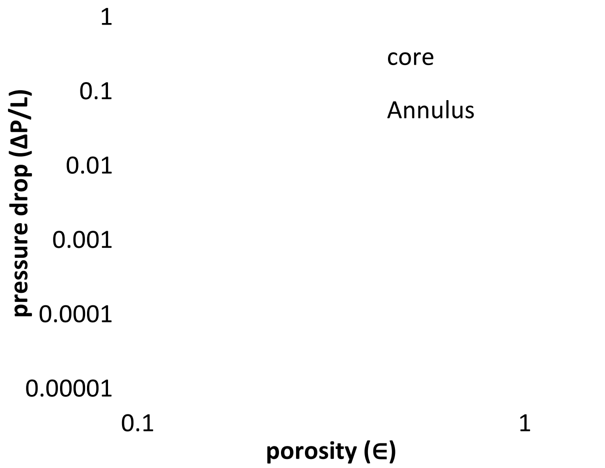

Fig.4 .(a) Pressure drop against porosity for bed to particle diameter ratio (D/d)= 13 for mass flow rate of 0.025 and particle diameter of 5mm

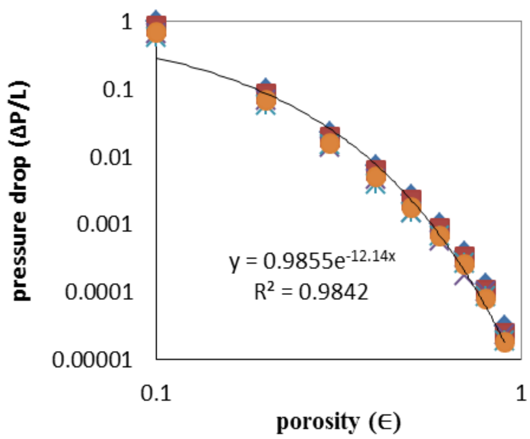

Fig.4 (b) correlation plot for pressure drop against porosity.

$$\Delta P/L = 1.1955e^{-12.03\epsilon} \qquad D/d > 13 \qquad (3)$$

Further investigation on different shape beds is required to conclude that this holds good for other shapes of porous medium too. Furthermore, the influence of particle diameter on Pressure drop is verified by varying the diameter of particles from 0.1 to 10 mm , Fig.4 (a) & (b) Demonstrates the variation of pressure drop **(ΔP**) against particle diameter ranging from 0.1to 1 mm Correlations are developed from scattered plots Fig. 5(a) & (b) for instance it is clear that the value of Pressure drop decreases with increase in size of the particles used in the formation of porous media. The resulting regression equations show that for every additional increase of D_p will decrease the pressure drop. The Anova tables are generated for regression analysis for both the plots The regression analysis is shown in ANOVA table, Where SS indicates sum of squares, MS is Mean square, df is Degree of freedom and F is the ratio of MSR/MSr. Where MSR is Mean square due to Regression and MSr is Mean square due to Residual. The amount of variability in the data is shown by R-squared value. high R-squared indicates that the maximum.

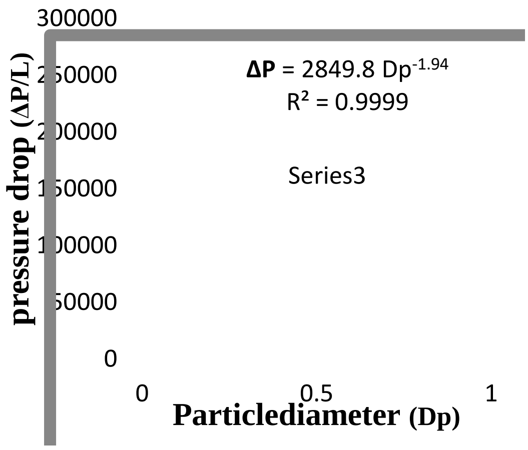

Fig.5 (a) Pressure drop against particle diameter (0.1-1)

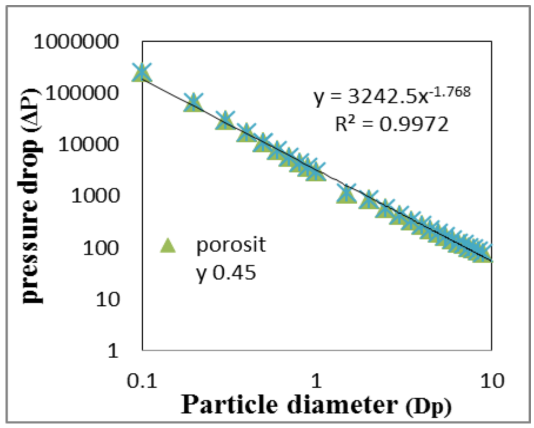

Fig.5. (b) Pressure drop against particle diameter (1-10)

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of the data variability is clearly explained by the model. The significant F-test suggests that there is a non-zero regression coefficient By considering the effects of porosity, bed to particle diameter ratio and particle diameter, Correlation analysis for data obtained, has been done to obtain the relation between pressure drop and velocity (Fig.6). The Pearson-Correlation Coefficient value shows that the relation for both core and Annulus positions of porous media relation is positive relation.i.e pressure drop is directly promotional to velocity. Regression analysis gives the following correlations.

(a) $\Delta P/L = 1.55v^2 - 0.603v + 0.0533$ $(R^2=0.9993)$ (4)

(b) $\Delta P/L = 1.669\, v^2 - 0.747v + 0.0753$ (R2= 0.9987) (5)

Table. 3 Anova Table for Fig .4 (a)

ANOVA						
	df	ss	MS	F	Significance F	
Regression	1	33379697.09	33379697	7.034915	0.017385943	
Residual	16	75917779.35	4744861			
Total	17	109297476.4				
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	3528.104575	1071.190971	3.293628	0.00458	1257.281159	5798.927991
X Variable 1	-524.9576883	197.9223604	-2.65234	0.017386	-944.5343491	-105.3810276

Table.4 Anova Table for Fig .4 (b)

ANOVA						
	df	SS	MS	F	Significance F	
Regression	1	0.291631	0.291631	6.620026	0.03685	
Residual	7	0.308369	0.044053			
Total	8	0.6				
	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.603852	0.080771	7.476111	0.00014	0.412859	0.794844
X Variable 1	-2.4E-06	9.19E-07	-2.57294	0.03685	-4.5E-06	-1.9E-07

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IV. CONCLUSIONS

In the present study an indusial correlations are obtained for pressure drop against porosity, bed to particle diameter ratio and particle diameter. The empirical correlations obtained are helpful to study the effect of all these parameters on pressure drop. It can be seen that the pressure drop for same mass flow rate decreases when the bed to particle diameter ratio and particle size increases and this continues up to (D/d) ratio reaches maximum value (13). Where the effect of shape of the porous medium on pressure drop is negligible. Finally general correlations are obtained for pressure drop against velocity by considering the effects of all the three parameters.

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AUTHORS PROFILE

Mr. Siva Murali Mohan Reddy.A is Assistant Professor in the Department of Mechanical Engineering at Sapthagiri College of Engineering, Bangalore, Karnataka state, India. He is perusing PhD at Visvesvaraya Technological University, Belgaum, under the guidance of Dr. Venkatesh M. Kulkarni, Profesor in the Department of thermal power engineering at VTU Centre for Postgraduate Studies, Gulbarga, Karnataka, India. His area of research is Investigations on Heat and Fluid flow in porous media for industrial applications. He completed Masters in Thermal Power Engineering from P.D.A College of Engineering, Gulbarga, affiliated to Visvesvaraya Technological University, Belgaum. in 2006 .He is also having more than 12 years of experience in teaching and industry, and his work has been published in 12 peer revived journals and 3 conferences.

Dr.Venkatesh M.Kulkarni, PhD is Professor in the Department of thermal power engineering at VTU Centre for Postgraduate Studies, Gulbarga, Karnataka state , India. He completed his PhD from University Sains , Malaysia in Thermo fluids in the year 2006, and worked as a Post-Doctoral Fellow at

Nationl Cheng Kung University (Taiwan) for more than one year. He is having 13years experience in teaching and industry, with 4 years of post-PhD research experience. He is reviewer to International Journal of Heat and Mass Transfer (ELSEVIER). IEEE Transactions on SENSORS ,Journal of Petroleum and Gas Engineering, MDPI Journal on SENSORS. He is also life time member of American Society of Mechanical Engineers (ASME) and Indian Society for Heat and Mass Transfer (ISHMT). He has published more than 20 peer review research articles and 8 conference papers. He is Expertise in FEM formulation, code development for mesh/grid generation, solver and post processing for any type of given physical phenomenon using MATLAB/FORTRAN, his other areas of interest are, Computational Fluid Dynamics and Heat Transfer., thermo-fluid-mechanical analysis of electronic packages. Thermal management techniques for cooling of electronic devices, thermal modeling and analysis. Turbo machinery, numerical analysis methods, design optimization using Genetic Algorithm and Neural Networks. Design of advanced power plants, thermal systems, heat recovery equipment etc.