The 3rd TSME International Conference on Mechanical Engineering
October 2012, Chiang Rai

Axial Compression for Direct Capture of Carbon Dioxide (CO_2)

Hao Xian Malcolm Chan *, Eng Hwa Yap and Jee-Hou Ho

Department of Mechanical, Materials & Manufacturing Engineering, Faculty of Engineering, The
University of Nottingham Malaysia Campus, Jalan Broga, 43500 Semenyih, Selangor, Malaysia
*Corresponding Author: kedx1mca@nottingham.edu.my, +60 (0)3 89248 609

Abstract

There is growing concern that climate change is transforming into a problematic calamity globally and one of the major causes is the anthropogenic emission of greenhouse gases (GHGs) into the atmosphere. One prospective method, that has been extensively researched, to reduce the effect of climate change upon the environment is Carbon Capture and Storage (CCS). However, reducing emissions through generic CCS technology can only slow down the rate of increase of atmospheric CO_2 concentration. Such actions are not known to be able to mitigate the CO_2 that are already in the atmosphere by previous emissions. Hence, a complimentary method would be to extract CO_2 directly from air – Direct Air Capture (DAC). This paper addresses a novel development concept of DAC, whereby a phase of axial compression is introduced to adapt atmospheric air to a CO_2 concentration level best suited for existing CCS processes. A design process is initiated to develop an axial compression model where fluid simulation studies are performed. These information are then utilized to perform a feasibility study where several key issues are addressed: the additional energy penalty when applying axial compression and whether or not, increasing the capture input by compression would displace the elevated energy consumption.

Keywords: CCS; Direct Air Capture; feasibility study; axial compression.

1. Introduction

Annual global emissions of CO_2 have escalated by approximately 80% between 1970 and 2004 [1-2]. One prospective method that has been extensively researched to reduce the effect of climate change is Carbon Capture and Storage (CCS). Reducing emissions through generic CCS technology could potentially minimize emissions from point sources, but this could only slow the increasing rate of atmospheric CO_2 concentration. Such actions cannot mitigate the carbon already released the atmosphere by previous emissions. These are called distributed emissions, as these anthropogenic carbon sources have already been distributed across the atmosphere.

One specific method to address distributed emissions is extracting carbon dioxide directly from air known as Direct Air Capture (DAC). Since CO_2 is evenly mixed in the Earth's atmosphere, air capture can, in effect, capture CO_2 emitted from any location, using the atmosphere as a direct link between different emission sources and the air capture facility. The technology of DAC is not novel and is an extensively researched field of science. Although it was first suggested by researchers in 2001 [3], similar research studies have been conducted thereafter [4-9].

Capturing CO_2 from air has its own pros and cons. For example, DAC has a lower construction and energy cost as compared to conventional CCS technology and the location of DAC facilities are more flexible and can be built at more accessible locations [10]. Also, DAC systems need not be tightly integrated into existing energy-producing infrastructures. Furthermore, DAC can effectively remove CO_2 with equal ease or difficulty from all parts of economy because the technologies adopted for DAC application can be provided at fixed marginal costs [5]. However, the significantly lower concentration of CO_2 in atmospheric air renders DAC an engineering challenge [11]. The most critical problem is that the nearest concentration similar to atmospheric level of CO_2 concentration is post-combustion capture from coal flue gas, at a concentration of 5 – 15% [12] whilst DAC can only work with dilute concentration of CO_2 in atmospheric air at a mere 0.04% [13] concentration.

The recent trend in researching the technology of DAC involves creating new materials or processes [14-23] in order for DAC to improve as a more feasible and efficient process. An alternative approach, however, would be to create new technologies whereby atmospheric air can be adapted to a CO_2 concentration level high enough that it would suit any existing CCS processes. The aim of this paper is to propose an alternative approach to improve the efficiency of a DAC system whereby an axial compression scheme is integrated into a DAC system that would enhance the low input CO_2 concentration of 0.039%, thus further improving the efficiency of carbon capture operation.

2. Methodology

The methodology of the case study proposed is separated into three different processes; compressor design, simulation, and feasibility study. The compression process is initially designed through a mathematical process to produce a complete compressor model with the necessary geometrical values. Using the designed compressor model, computational fluid simulation is then performed to obtain the actual end CO_2 concentration after going through a compression phase. These end concentration results could then be utilized in the feasibility study to demonstrate the total energetic transfer in between the different processes in the said DAC system.

Axial compression is selected as a basis for the compression design since it is a mature technology and holds a large knowledge base. There are other more recent compression technologies in the industry [14-16], however, these newer developments are not technologically matured and still require further understanding. Axial compression achieves considerably higher pressure ratio at a higher level of efficiency. It can also handle a much larger mass flow compared to a radial flow compressor. Axial flow compressors can also achieve higher thrust per unit frontal area where modern axial flow compressors may give efficiencies of up to 86–90% [18].

To perform energy and cost analysis for the proposed method, a reference system would be utilized where the information of the DAC technology applied as well as the chemical/thermodynamic processes available in literature. The feasibility of the system would be assessed by summing energetic penalty exerted by the system and the total carbon content captured. The study by Bachiocchi [24-25] features the absorbing technology; caustic recovery, found in literature [5] with absorbing columns utilizing electric fans to maintain constant draw-in velocity. The reference plant[13] for this study was chosen because it utilizes existing engineering technology in CCS and detailed information on material and energy balances are easily available.

The proposed method aims to replace the electrical fan with an additional compressor that would pressurize the air intake before undergoing the chemical process with absorption liquid. It is envisaged that such a method would greatly increase the input CO_2 concentration over existing method using electric fan. However, the additional process of compression would introduce an additional energetic penalty. The notion of the scheme is that by increasing the capture input by compression, it will reduce energy and cost related separation parameters, leveling or surpassing the energetic penalty of additional compression.

2.1 Compressor Design

Design process was initiated to form a compressor model utilizing a combination of thermodynamic and aerodynamic correlations, constituent formulae, compressor performance coefficients and compressor design specifications.

Literature are also utilized in the process [29-31] as well as other fundamental thermodynamic theories such as the Steady Flow Energy Equation (SFEE) to investigate heat and work transfer [32] from which the temperature and pressure properties of the compressor are computed. Thermodynamic properties such as C_p (specific heat capacity at constant pressure) and γ (heat capacity ratio) are calculated using NASA's chemical equilibrium model [33-34].

2.2. Computational Modeling and Simulations

The analytical method would yield a set of compressor performance parameters. By applying methods found in literature [29-31], a set of geometrical related properties such as thickness chord ratio, and normalized spacing for the compressor profile are obtained and utilized to build a simulation model. Based upon references [35-39] of the NACA-65 blade series, the geometry of the blade can also be computed from the lift coefficient.

A validation test is then conducted to verify the simulation settings using the NACA-65 series airfoil blade experimental data by Briggs [40].

The comparison results are shown in Fig. 1. The data obtained correlate closely with the experimental data with a slight over-prediction at the trailing edge (from a distance 0.4 of the chord lengths onwards) of the airfoil. Compared to Briggs', the simulated data do not deviate much, hence verified the simulation setting. As for the leading edge, the simulated results predicted the peak coefficient of pressure at around 0.05 chord length while the experimental data shows the peak at a distance 0.1 chord length from the nose of the airfoil.

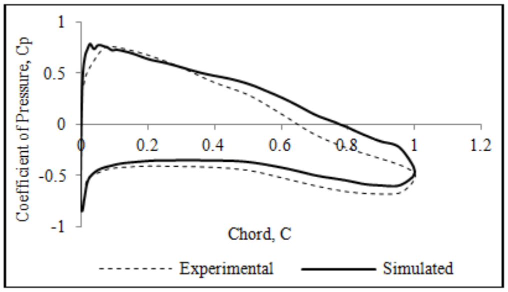

Fig. 1 Experimental and Simulated Coefficient of Pressure (C_p) for NACA 65-(12)10

2.2.1 Initial and Boundary Conditions

Once benchmarking is completed, a 2D single-stage axial compressor with NACA 65-(12)10 airfoil blade is modeled and simulated. Fig. 3 shows the model of the 2D compressor domain for the axial compressor. The inlet and outlet of the simulation domain are based upon the computed blade spacing and the compressor blade has a total of one chord length.

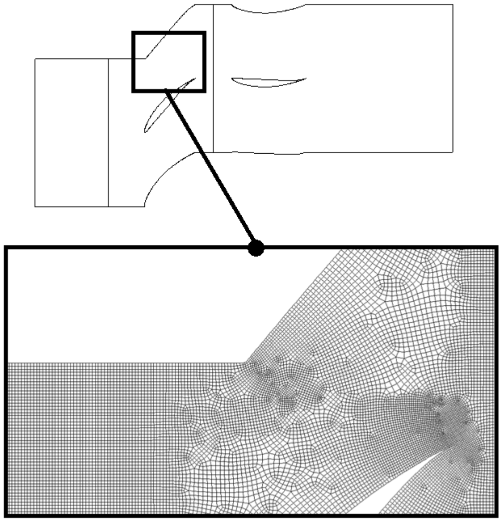

Fig. 2 Final Compressor Model and Partial Mesh Configuration

The numerical simulation runs were made with the assumption of unsteady, two-dimensional, turbulent and incompressible flow. Ideal gas theory is applied and other fluid properties are set constant. The simulations were made at Mach Number, Ma= 0.46, pressure ratio of 1.1 and Reynolds Number, Re= 11.4 x 10^6.

2.2.3. Numerical Solution Procedure

The turbulence models utilized for this simulation is Reynolds Stress Model (RSM). The time step size selected is 4x10^{-6} second for 20000 time steps. This is equivalent in simulation procedure as 20 repetitive cycles of compressor rotation, where the simulated compressor has reached steady state condition. The central differencing scheme is used for the diffusion terms. The discretized equations were solved based on pressure correction method and uses PRESTO! (Pressure Staggering Option) algorithm [41]. First Order Upwind discretization scheme [42-43] is selected for convection-diffusion formulation. PISO algorithm is used for Pressure-Velocity Coupling Method. Under-relaxation factors are used to increase stability in time-stepping.

3. Results and Discussion

3.1 Simulation Results

From Fig. 3, it can be observed that the simulation results provide a visualization of the compression process described by the mathematical model. The pressure contour in Fig. 3(a) shows a rise in pressure, displaying a pressure ratio of 1.1 – 1.3 as intended in the boundary conditions inserted. The normalized molar concentration of CO_2 also displays a total increase in CO_2 concentration of 10% at the near end region of the compressor. The CO_2 concentration incremental in simulation results can then be utilized in the feasibility study.

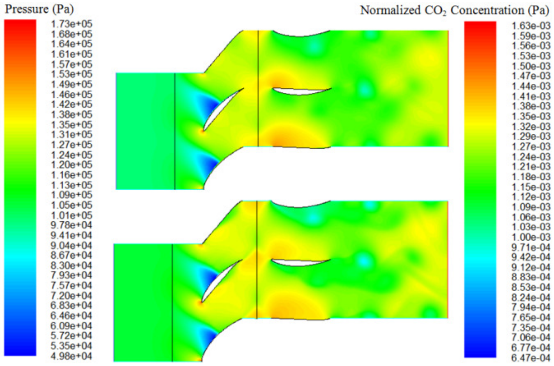

Fig. 3. (a) Pressure and (b) CO_2 Molar Concentration of Axial Compressor Simulation

3.1 Feasibility Study

Feasibility study can then be conducted utilizing the reference capture system discussed in the Methodology section.

Capturing process for the reference plant occurs in cylindrical absorbers sized 12 m in diameter, 2.8 m in length, and 2 m/s velocity of the air through the absorber. 0.28 Mt/h of 2 mol NaOH solution is used as capturing solution at a density of 1,080 kg/m^3. With liquid-to-gas mole ratio of 1.44 mol/mol and 8,000 operational hours per year, the system is assumed to work in atmospheric air of 0.049 % CO_2 concentration with 50% efficiency. The number of absorbers required is approximately 347. The capturing operation amasses an electrical energetic penalty of 1.744 GJe/t-CO_2 where the script Je represents electrical energy. The electrical energy consumption comprises of either the absorber fans or the axial compressor, other ancillary processes such as slaking, precipitation, as well as air separation.

By replacing the electric fans with axial compressor, certain information in the analytical studies are replaced. For example, axial compressor provides a higher concentration in the atmospheric feed into the capturing system, as well as increasing the velocity of the gas flow into the absorber column. Both these qualities will reduce the capturing process time, but increase the kilowatt consumption.

It should be noted that the calculation for the enhanced compression is applied quantitatively for all absorbers, meaning that each absorber is coupled with a compressor unit. Also, the thermodynamic effect of absorption between pressurized air and absorption liquid at elevated pressure is overlooked.

Table. 1 Comparison of Process Data for the Enhanced Mode of DAC

Specifications	Units	Default	Enhanced Mode
Plant Capacity	Mt/yr	1	1
CO2 concentration in	% vol	0.049	0.231
CO2 concentration out	% vol	0.025	0.115
Time on-stream	h/yr	8,000	8,000
No of absorbers	-	347	1
Total CO_2 Captured	t/h	125	125
Gas velocity	m/s	2	270
Axial Compressor	GJe/tCO2	-	1.257
Absorber fans	GJe/tCO2	0.633	-
Other Processes	GJe/tCO2	0.916	0.916
CO2 compression	GJe/tCO2	0.195	124.280
Electricity subtotal	GJe/tCO2	1.744	126.453

Table. 1 presents the comparison between the reference plant system (Default) and plant replaced with axial compression system (Enhanced Mode). It shows a reduction of absorber columns to 1 in the enhanced mode due to increased input CO_2 concentration as the increasing gas velocity accelerates the capturing process.

However, the electrical energy consumption for the Enhanced Mode was driven to a high level at 126.453 GJe/tCO_2. This is because the high velocity of air passing causes the CO_2 compressor to operate at higher energy consumption even though the amount of absorbers is reduced. In order to create a sustainable enhanced mode, the capture yield must be made larger. A different set of results were produced whereby the electrical energy consumption was equalized in order to juxtapose the effect of the enhanced mode.

As can be seen in Table. **2**, the subtotal electrical energy consumption for both the default and enhanced mode has been equalized. By utilizing 1.941 GJe/tCO_2, the default case could only capture an annual CO_2 capacity of 0.5 Mt/yr where as the enhanced mode manages a plant capacity of 366 Mt/yr which is 732 times more than the default case. After the compression enhancements, the CO_2 captures per absorber for the enhanced mode is still higher (at 228.91 t/h) even though the amount of absorbers was increased for about 15% from the default case.

Table. 2 Comparison of Process Data with Equalized Electrical Energy Consumption

Specifications	Units	Default	Enhanced Mode
Plant Capacity	Mt/yr	0.5	366
CO2 concentration in	% vol	0.049	0.231
CO2 concentration out	% vol	0.025	0.115
Time on-stream	h/yr	8,000	8,000
No of absorbers	-	174	200
CO_2 captured/absorber	t/h	0.36	228.91
Gas velocity	m/s	2	270
Axial Compressor	GJe/tCO2	-	0.686
Absorber fans	GJe/tCO2	0.635	-
Other Processes	GJe/tCO2	0.916	0.916
CO2 compression	GJe/tCO2	0.391	0.339
Electricity subtotal	GJe/tCO2	1.941	1.941

It is apparent here that larger CO_2 yield must be utilized in order to fully capitalize the true effectiveness of the compression enhancement. As the initial CO_2 concentration and air velocity is significantly elevated, the energy consumed would not be strategic only to capture a small portion of CO_2 where the enhanced mode would be underutilized. The perfect scenario between plant capacity and electrical energy consumption should be a linear relationship.

However, it should be noted that the feasibility studies is still in its early stage. Even though the feasibility studies show that an axial compression phase provides a competitive edge for a DAC system over its default form, its performance is still sub-par compared to a conventional plant utilizing post-combustion capture (PCC) [44]. To accurately assess the true potential of the concept, further analytical research on a designated multi-stage compressor is required, as well as more detailed analysis on the material and energy balances of an air capture reference system.

4. Conclusion

By utilizing axial compression, this paper analyzed the efficiency of a DAC system featuring standard absorption processes. A DAC system coupled with axial compression shows sign of improvement in capturing efficiency but not without rooms for improvement when compared with conventional post-combustion capturing process. Such a system requires optimization of the capturing processes, in-depth energetic analysis, as well as developing a more detailed axial compression model, which are considered key enablers to determine the feasibility of axial compression as a CO_2 enhancing method in DAC.

6. Acknowledgement

The authors would like to acknowledge the Ministry of Higher Education (MOHE), Malaysia for their sponsorship of this research project through the Fundamental Research Grant Scheme (FRGS).

7. References

[1] Stern, N. (2006). *Stern Review on the Economics of Climate Change*. Cambridge : Cambridge University Press.

[2] Metz, B., Davidson, O., de Coninck, H., Loos, M., & Meyer, L. (2005). *Intergovernmental Panel on Climate Change. Special Report on Carbon Dioxide Capture and Storage.* Cambridge: Cambridge University Press.

[3] Lackner, K. S., Grimes, P., & Ziock, H.-J. (2001). Capturing Carbon Dioxide from Air. *First National Conference on Carbon Sequestration.* Washington DC: National Energy Technology Laboratory.

[4] Herzog, H. (2003). *Assessing the Feasibility of Capturing CO2 from the Air.* Cambridge: Laboratory for Energy and the Environment, Massachusetts Institute of Technology.

[5] Keith, D., Ha-Duong, M., & Stolaroff, J. (2005). Climate Strategy with CO2 Capture from the Air. *Climatic Change* , 74(1-3): pp. 17-45.

[6] Mahmoudkhani, M., & Keith, D. W. (2009a). Low-energy sodium hydroxide recovery for CO2 capture from atmospheric air—Thermodynamic analysis. *International Journal of Greenhouse Gas Control 3* , pp. 376-384.

[7] Mahmoudkhani, M., Heidel, K. R., Ferreira, J. C., Wdas, K. D., & Cherry, R. S. (2009b). Low energy packed tower and caustic recovery for direct capture of CO2 from air. *Energy Procedia I* , pp. 1535-1542.

[8] Stolaroff, J. K., Keith, D. W., & Lowry, G. V. (2008). Carbon Dioxide Capture from Atmospheric Air Using Sodium Hydroxide Spray. *Environmental Science & Technology* , pp. 2728-2735.

[9] Wang, T., Lackner, K. S., & Wright, A. (2011). Moisture Swing Sorbent for Carbon Dioxide Capture from Ambient Air. *Environmental Science & Technology* , pp. 6670-6675.

[10] Thompson, J. M. T., Launder B. (2009). *Geo-Engineering Climate Change: Environmental Necessity or Pandora's Box?*. Cambridge: Cambridge University Press.

[11] D'Alessandro, D. M., Smit, B., & Long, J. R. (2010). Carbon Dioxide Capture: Prospects for New Materials. *Angewandte Chemie International Edition* , 49, pp. 6058 – 6082.

[12] Rackley, S. (2010). *Carbon Capture and Storage*. Burlington: Elsevier

[13] Tans, P., & Keeling, R. (2012). *Trends in Atmospheric Carbon Dioxide*. Retrieved from Earth System Research Laboratory, Global Monitoring Division, URL:http://www.esrl.noaa.gov/gmd/ccgg/trends/, access on 20/05/2012

[14] Yave, W., Car, A., Funari, S. S., Nunes, S. P., & Peinemann, K.-V. (2010). CO2-Philic Polymer Membrane with Extremely High Separation Performance. *Macromolecules*, vol.43, pp. 326–333.

[15] Adams, R., Carson, C., Ward, J., Tannenbaum, R., & Koros, W. (2010). Metal organic framework mixed matrix membranes for gas separations. *Microporous and Mesoporous Materials* .

[16] Belmabkhout, Y., Serna-Guerrero, R., & Sayari, A. (2010). Amine-bearing mesoporous silica for CO2 removal from dry and humid air.

Chemical Engineering Science, pp. 3695-3698.

[17] Blasucci, V., Dilek, C., Huttenhower, H., John, E., Llopis-Mestre, V., Pollet, P., et al. (2010). Single component, reversible ionic liquids for energy applications. *Fuel* , vol.89(6), pp. 1315-1319.

[18] Finamore, N. K., Liu, C., Mohanty, P., Moore, D. T., & Landskron, K. (2010, September 9). Electric Field Swing Adsorption for Carbon Capture Applications. Bethlehem, Jerusalem, Israel.

[19] Hudiono, Y. C., Carlisle, T. K., Bara, J. E., Zhang, Y., Gina, D. L., & Noble, R. D. (2010). A three-component mixed-matrix membrane with enhanced CO2 separation properties based on zeolites and ionic liquid materials. *Journal of Membrane Science* , vol.350, pp. 117–123.

[20] Liu, Y., Hu, E., Khan, E. A., & Lai, Z. (2010). Synthesis and characterization of ZIF-69 membranes and separation for CO2/CO mixture. *Journal of Membrane Science*, vol.353, pp. 36–40.

[21] Liu, Z., Grande, C. A., Li, P., Yu, J., & Rodrigues, A. E. (2011). Multi-bed Vacuum Pressure Swing Adsorption for carbon dioxide capture from flue gas. *Separation and Purification Technology*, vol.81(3), pp. 307-317.

[22] Lu, Y., Yea, X., Zhang, Z., Khodayari, A., & Djukadi, T. (2011). Development of a carbonate absorption-based process for post-combustion CO2 capture: The role of biocatalyst to promote CO2 absorption rate. *Energy Procedia*, vol.4, pp. 1286–1293.

[23] McIntyre, J. A., Ebner, A. D., & Ritter, J. A. (2010). Experimental study of a dual reflux enriching pressure swing adsorption process for concentrating dilute feed streams. *Industrial & Engineering Chemistry Research*, vol.49, pp. 1848–1858.

[24] Socolow, R., Desmond, M., Aines, R., Blackstock, J., Bolland, O., Kaarsberg, T., et al. (2011). Direct Air Capture of CO2 with Chemicals A Technology Assessment for the APS Panel on Public Affairs. Maryland: American Physical Society.

[25] Baciocchi, R., Storti, G., & Mazzotti, M. (2006). Process design and energy requirements for the capture of carbon dioxide from air. *Chemical Engineering and Processing*, pp. 1047 - 1058.

[26] J. Ciferno J. Litynski L. Brickett J. Murphy R. Munson C. Zaremsky J. Marano J. Strock, (2011), DOE/NETL Advanced Carbon Dioxide Capture R&D Program: Technology Update, Albany: U.S. Department of Energy, National Energy Technology Laboratory.

[27] Harkin, T., Hoadley, A., & Hooper, B. (2011). A comparison of the Process Integration of Shockwave CO2 compression with conventional turbo machinery into PCC power station design. *Energy Procedia*, vol.4, pp. 1339–1346.

[28] Ciferno, J. P., Fout, T., & Nicolet, D. (2011, February). Ramgen Supersonic Shock Wave Compression and Engine Technology. Albany: NETL/DOE.

[29] Dixon, S. L., & Hall, C. A. (2010). *Fluid Mechanics and Thermodynamics of Turbomachinery.* Kidlington: Elsevier.

[30] Gorla, R. S., & Khan, A. A. (2003). *Turbomachinery Design and Theory.* New York: Marcel Dekker, Inc.

[31] Logan, E., & Roy, R. (2003). *Handbook of Turbomachinery.* New York: Marcel Dekker, Inc.

[32] Cengel, Y., & Boles, M. (2010). *Thermodynamics: An Engineering Approach.* New York: McGraw-Hill Companies, Inc.

[33] Gordon, S., & McBride, B. J. (1994). *Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications I. Analysis.* Cleaveland: National Aeronautics and Space Administration.

[34] Gordon, S., & McBride, B. J. (1996). *Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications II. Users Manual and Program Description.* Cleveland: National Aeronautics and Space Administration .

[35] Ladson, C. L., & Brooks Jr., C. W. (1974). *Development of a Computer Program To Obtain Ordinates for NACA 6- and 6A-Series Airfoils.* NASA TM X-3069.

[36] Ladson, C. L., Brooks Jr., C. W., Hill, A. S., & Sproles, D. W. (1996). *Computer Program To Obtain Ordinates for NACA Airfoils.* Hampton: National Aeronautics and Space Administration.

[37] Abbott, I. H., & Von Doenhoff, A. E. (1959). *Theory of Wing Sections.* New York: Dover Publications Incorporated.

[38] Jacobs, E. N., Pinkerton, R. M., & Greenberg, H. (1937). *Tests of Related Forward-Camber Airfoils in the Variable-Density Wind Tunnel.* Naca Report No. 610.

[39] Theodorsen, T. (1931). *Theory of Wing Sections of Arbitary Shape.* NACA Report No. 411.

[40] Briggs, W. B. (1952). *Effect of Mach Number on the Flow and Application of Compressibility Corrections in a Two-Dimensional Subsonic-Transonic Compressor Cascade having Varied Porous Wall Suction at the Blade Tips.* Cleveland: National Aeronautics

and Space Administration.

[41] Issa, R. I. (1986). Solution of the Implicitly Discretised Fluid Flow Equations by Operator

[42] Patankar, S. V. (1980). *Numerical Heat Transfer and Fluid Flow*. New York: McGraw-Hill.

[43] Versteeg, H. K., & Malalasekera, W. (1995). *An introduction to Computational Fluid Dynamics*. New York: Longman.

[44] M., Ramezan, et al.. (2007). Carbon Dioxide Capture from Existing Coal-fired Power Plant. Pittsburgh: US Department of Energy–National Energy Technology Laboratory.