COMPUTATIONAL ANALYSIS OF CYCLONIC SEPARATION

by

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B.S., Mechanical Engineering, Azad University of Tabriz, 2004

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Computational Science and Engineering
Boğaziçi University
2014

ACKNOWLEDGEMENTS

I would like to express my special thanks to academic staff at Bogaziçi University. They encouraged me during my research and help me to grow as an academic researcher. I would like to present my appreciation to Prof. Emre Otay, whose advice on both research as well as on my career have been priceless and wonderful. I would also like to thank my committee members, Prof. Günay Anlaş, Prof. Levent Kurnaz for serving as my committee members, letting my defense be an enjoyable moment, and for their brilliant comments and suggestions. I would especially like to thank Farhad Kazemi kh., Kaveh Shahidi, Ramin F. Fouladi, Nima Shafaghi, Niyazi Tanlak, Fatih Ertuğrul Öz, Erhan Yücel and Merve Baltaci who have aids for my approaches to the subject of this thesis. Also, I would like to present my appreciation to Oya Özağaç and Parisa Behzadi for editing of my thesis. And special thanks to Arda Kocaman and Eti Bilgisayar corporation for their vital helps in COMSOL. All of you have been with me to support me when I faced problems and collected data for my Master thesis.

Last but not least, I would like to thank to my family. Words cannot express how grateful I am to my mother and father for all the sacrifices they have made on my behalf. Their prayer for me was what sustained me thus far. I would also like to thank all of my friends who supported me, and encouraged me to strive towards my goal. Finally, I would like express my appreciation to my beloved girl friend, Haniyeh Behzadi for her emotional help and being supportive in the moments when there was no one to answer my queries.

ABSTRACT

COMPUTATIONAL ANALYSIS OF CYCLONIC SEPARATION

Cyclonic separation is a method to remove particles from a fluid flow using a vortex for separation. This method of separation can be used to separate fine droplets of liquid or particles from a gas flow. This device is a kind of stationary mechanical device that uses centrifugal force to separate any kind of particles from a fluid stream. There are two fundamental types of air cyclones according to the direction in which the cleaned gas leaves the cyclone. The reverse flow cyclone is one of them and it is actually the most frequently used type in industry. While the clean gas leaves from upper lid, separated particles can exit through a bottom apex. Cyclones have simple manufacturing, low energy requirements, capability to work at high pressures and temperatures. In spite of the simplicity in manufacturing and operation, the mathematical formulations used for anticipating the separation efficiency are very complicated. In contrast to most of the previous studies which use a single input, in this study two slot type cyclone separators are considered and compared together, for both laminar and turbulent flows. In this research, mathematical modeling of cyclonic separation is based on Muschelknautz Method formulation (MM) and the computational fluid dynamics (CFD) analysis is performed using the COMSOL Multi-Physics program. Some of the well-known models such as Muschelknautz D type, Swift High Efficiency, Stairmand High Efficiency and Lapple General Purpose with single and double inputs are analyzed and compared. A model with different input sizes with single and double inputs is introduced and parameterized in terms of pressure drop profile, velocity magnitude, number of particles that each cyclone can separate, separation efficiency and stream lines in laminar and turbulent streams. The particle tracing module of COMSOL is used for that purpose.

ÖZET

SİKLONİK AYIRMANIN NUMERİK ANALİZİ

Siklonik ayırma, vorteks kullanılarak bir akışkandaki parçacıklardan kurtulma yöntemidir. Bu ayırma yöntemi, bir gaz akışındaki parçacıkları veya ince sıvı parçacıkları ayırmak için kullanılabilir, ama gaz tipi siklonlar özellikle doğal gaz boru hatlarındaki katı parçacıkları veya egzozlardaki tozları ayırmak için kullanılır. Bu sabit cihaz, bir akıştaki herhangi bir parçacığı ayırmak için merkezkaç kuvvetini kullanmaktadır. Temizlenen gazın siklondan çıktığı yöne göre iki temel tip hava siklonu vardır; düz ve ters akışlı siklonlar. Düz siklonlarda, kirli hava silindirik kısmın bir ucundan girer ve öbür ucundan çıkar; bu tip siklonların endüstride kullanımı sınırlıdır. Ters akışlı siklonlar, endüstride en sık kullanılanlardır. Gaz girişi en tepeye yakın bir yerdeki teğet bir giriş boyunca olur ve eksenel olarak azalan bir gaz spiralinin ve merkezkaç kuvvet alanının gelen taneciklerin eksen boyunca yoğunlaşmasına ve ayırıcının iç duvarlarına düzenli biçimde düşmesine neden olur. Ayrılmış parçacıklar alt çıkıştan çıkarken temiz parçacıklar yön değiştirerek üst taraftan çıkar. Siklonlar bazen başka türlü filtrelerden daha verimsiz olabilir. Yine de diğer toz ve nem toplayıcılarına göre daha yüksek maliyetlere mal olur ama daha basit şekilde imal edilebilirler ve yüksek sıcaklık ve basınçlarda daha düşük enerji ile çalışırlar. Önceki çalışmaların birçoğu tek bir giriş kullanmaktadır ama bu çalışmada iki slot tipli siklon ayırıcı kullanılmaktadır, ve laminer ve türbülans akis için önceki çalışmalarla karşılaştırılmaktadır. Bu tip siklonlar endüstride, özellikle yüksek hız ve basınç şartları için oldukça uygundur. Bu çalışmada, siklon ayırma için Muschelknautz metot formülasyonuna (MM) dayanan bir matematiksel model geliştirilmiştir ve COMSOL programı ile hesaplamalı akışkanlar dinamiği (CFD) analizi yapılmıştır.

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a	Inlet slot height
A_R	total inside area of the cyclone contributing to fractional drag
b	Inlet slot width
C_D	Drag Coefficient
c_o	solid loading
c_{oL}	Mass Loading
D	Main cylindrical body diameter
D_c	Height of the conical section
D_d	Diameter of the dust exit
D_x	Diameter of the vortex finder
f_{air}	Friction Factor
f_r	wall roughness friction
Fr_x	Froude number
f_{sm}	smooth wall friction
H	Overall height of the cyclone
Re_p	Particle Reynolds number
Re_R	Cyclone Body Reynolds number
R_m	geometric mean radius
S	Length of the vortex finder(inside the cyclone)
U'_{t50}	Terminal velocity of the cut-sized particle rotating in CS
v_{in}	input velocity
$v_{\theta w}$	wall velocity
v_{zw}	wall axial velocity
$v_{\Theta m}$	Mean Rotational velocity
$v_{\theta CS}$	Inner Core velocity
x_{50}	Cut-Size diameter
α	constriction coefficient

ρ	gas phase density
ρ_p	solid phase density
ρ_{str}	Bulk density of the particles
μ	gas phase absolute viscosity
η	Collection Efficiency and Performance
Δp	Total Pressure Loss
Δp_{acc}	Acceleration pressure loss
Δp_{body}	Wall Loss
Δp_x	Loss in the vortex finder

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
CFD	Computational Fluid Dynamics
LDA	Laser Doppler Anemometry
LES	Large Eddy Simulation
MM	Muschelknautz Method of modeling
RANS	Reynolds Averaged Navier Stokes
RSM	Response Surface Methodology

1. INTRODUCTION

Cyclonic separation is a method to remove particles from a gas or liquid flow, using a vortex. This filter utilizes centrifugal force to segregate solid and liquid particles from a gas flow. The gravity force is very small in comparison with centrifugal force that its effect can be neglected. Air type cyclones are especially used to separate solid particles from natural-gas pipelines or to filter dusts from exhaust stacks.

Cyclones are usually less efficient than other kinds of filters, but they are simple to be manufactured, have low energy requirements and are capable to operate at high temperature and pressure. In spite of the simplicity in construction and operation, complicated mathematical formulations are used for predicting the collection efficiency of particles due to the diameter of particles.

There are several types of cyclones based on the overall shape, inlet and outlet direction, however two major groups have been playing a main role in cyclonic separation. These two types are grouped according to the direction of inlet and outlet fluid flow in/out of the cyclone. One of them is "reverse flow" and the other is "straight through." The specification of the first type is that the input fluid tangentially enters the cylindrical part of the cyclone and after establishing the vortex, changes its direction and the clean air goes out through a vortex finder pipe. Position of this pipe is in the central section of the cyclone. The main body of this cyclone type consists of two essential sections: cylindrical and conical sections which are welded together. The output of separated particle is usually in the lower part of these types of cyclones which is called bottom apex or under flow section. This thesis is focused on the reversed flow cyclone as a result of more usage in industry. On the other hand, "straight-through cyclone" has other specifications that are completely different from the other types. In this model, the fluid enters from one face of the cylindrical body in the cyclone and leaves on the other side of the pipe. Because this type of cyclone is not used in industry, it is out of scope of this study [1].

There are numerous studies on the cyclone separator, and they are categorized in different groups, such as body shape, inlet types, pressure drops and separation efficiency. Each group has its own advantages and drawbacks. The main category of inlet section has four members: axial, helical or spiral and tangential. These groups have some pros and cons but generally, all of them establish a vortex stream inside the cylindrical part of cyclone, and the spin changes its direction after touching the conical part.

Cyclones can be found in both heavy and light industrial applications and can be used as either classifiers or separators. Powder coating, plastic fines, saw dust, wood chips, sand, rock and mineral crushing and various processing units, and liquid components from scrubbing and drilling operations are some examples of the applications of cyclones as separator or classifier [1].

This research aims to provide an overview of the varieties of cyclone body shapes, which is an important issue of separation technology. Theory and design methods are presented covering the important classical topics, including particle cut-size, grade efficiency, overall efficiency and pressure drop. There are diversities of design methods and theories. In this study, Muschelknautz modeling technique is selected. In addition, the following topics that are associated with cyclone structures are discussed:

- Importance of cyclone separation and pressure drop models
- Computational Fluid Dynamics (CFD) modeling
- Introducing a new model and comparing it with some well-known models
- Cyclone dimension and the natural vortex length
- Total collection efficiency
- Pressure drop during filtration
- Comparing single input with double one

The modeling approach was investigated by Walter Barth, and further developed by Edgar Muschelknautz and his co-workers [1]. Even with today's modern tools, we should accept that the cyclone's behavior is more complicate than we thought before. Each testing method showed new attitude of cyclone. In order to understand the phenomena governing their behavior, experimental studies, mathematical modeling and even computational fluid dynamics (CFD) modeling are required. However, in this thesis experimental output and results are not covered. Gas cleaning and cyclone technology are the basic concepts of the researches about the centrifugal separators. The dimensional analysis is the main key point for understanding cyclone technology and the basis for cyclone modeling and scaling. Computational fluid dynamics (CFD) simulation of fluid and particle in cyclone has become a brilliant point, and it has fair advantages for understanding the details of the flow inside the cyclones, but also there are some limitations in terms of accurate performance in the modeled cyclones. Obviously, the design of cyclonic systems requires some experiences in many areas of the physical sciences and engineering disciplines. Cyclones can be manufactured from a wide variety of materials, including carbon steel, stainless steel and any kind of alloys, or they may be made from castings, and some are molded-in plastic. Based on the conditions that are required in many work places, they may be covered by rubber, fluorocarbon, or especially hardened metal liners or electro-polished surfaces. Meanwhile, cyclones are particularly well suited for high pressure applications and severe solids and liquid loadings, where filter media is sensitive to abrasion, sparks, oil, humidity and temperature, and in applications wherein the separator must operate unattended for extended periods of time-up for several years in some refinery processing units [1]. Experience demonstrates that the more understands and learns about cyclones, and the more performance and equipment experience one obtains, the more successful and outstanding one becomes in applying his knowledge in a laboratory or operating plant environment. With this knowledge, some of the mysteries surrounding these deceptively simple looking devices will vanish [1].

In other words, the cyclone is one of the most dignified pieces of engineering design, of the particle technologist's art. There is an equipment with no moving parts and essentially no maintenance, which enables particles of micrometers in size to be separated from a gas moving at high speed, and without an enormous pressure-drop. It gets better: the harder it is driven (up to a point), the better in the efficiency; the heavier in the particle loading, the less in the pressure drop. That is why cyclones have become ubiquitous in the process. In power generation and innumerable manufacturing plants, they are at the first defense line of the environment. For air intakes to turbines on trains and helicopters, they are essential components. Even at home they are enabling vacuum cleaning without frequent bag cleaning at the moment.

1.1. BASIC CONCEPTS

1.1.1. Historical background

According to the reports, the first design was equipped with an extraction system incorporating cyclones at the Renault car factory in France, in late 19th century, but the idea should go back much further than that apparently to the flour milling industry. Their subsequent development is an interesting story for design evolution, with largely empirical optimization studies being carried out simultaneously and independently in the USA (Lapple, Leith and others), the UK (chiefly Stairmand), Japan (Iinoya and others) and the Eastern bloc countries. It could seldom have been more clearly demonstrated that good engineering will converge on the same range of designs, wherever it is performed [1].

Understanding how the cyclone works and how individual particles react within, it has been slow in following these pioneering industrial developments. Little had been done until the invention of the measuring equipment necessary to measure fluid velocities within the cyclone (particularly laser Doppler anemometry-LDA), the assembly of theoretical models (largely in Germany, by Barth, Muschelknautz, Loffler and others), and ultimately, the development of computational fluid dynamics (CFD) codes (pioneered by Swithenbank) which could accurately model swirling flows. Armed with these devices and techniques, it became clear that cyclones are, in fact, far from simplicity, and there is still much to learn. At the same time, new methods have been found and new designs have been developed [2].

According to some documents about cyclone's patent, the first cyclone was designed in 1885 in the USA by John Finch. He designed this cyclone for a company called Knickerbocker Co. Albeit; the name of this device was not the cyclone but assigned name was "dust collector," Figure 1.1, the working process of this device is so similar to cyclone that we use them in our life [1].

Thus, in first decade of 1800, there was a profound idea to use centrifugal force to separate the particles that exist in the mixtures of fluid flow. Finally, according to the basic rules in the physics, particles that carry in the fluid flow, can be settled when the main stream loses its momentum or velocity. Finch's analyses are based on the mentioned rule. That's why, he presented a settlement chamber based on the centrifugal force principles for slowing down the motion of particle instead of using the gravity forces. This elegant discovery remains one of the most precious investigations [1].

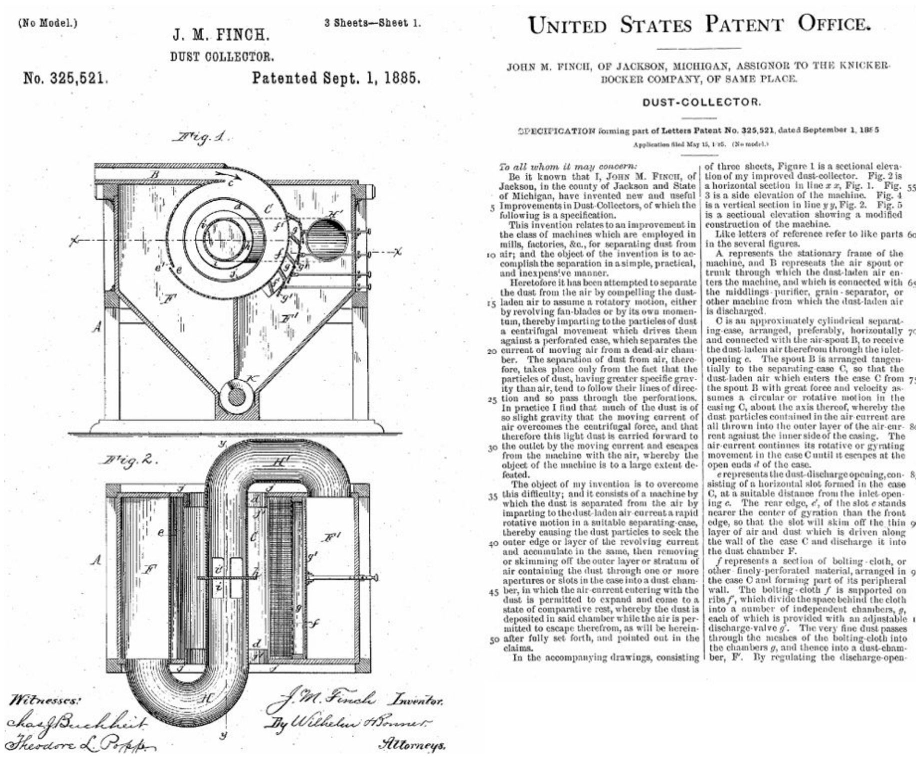


Figure 1.1. Patent documentation of the first cyclone [1].

Enhancements in the design of cyclones rapidly pursued. By early 1900s, cyclonic devices that were so similar to today's modern cyclones began to appear, such as, O. M. Morse in 1905, Rube-Goldberg in 1920 and many other patents. Most of these cyclones were used in the flour mill factories [1]. Comparing today's cyclones with some primary ones, same concepts can be observed. See more figures of patents and new version of cyclone separators illustrated in Figures 1.2, 1.3, 1.4 and 1.5 .

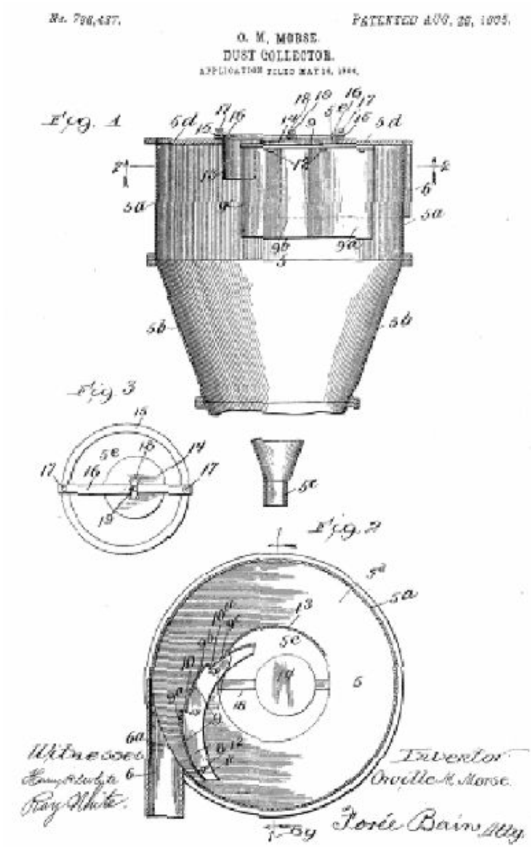


Figure 1.2. A basic patent of cyclone with conical section in bottom apex [1].

Many of the earlier cyclones were used to collect dust produced from mineral production such as zinc or mills that refined rocks or grains. During the decades, many industries noticed the need of removing particles from gas stream. Cyclone separators are used in modern industries, such as:

- Catalyst manufacturing plants
- Spray dryers
- Food plants
- Fossil fuel furnaces and wood-waste fired combustion units
- Breaking, grinding, separation and calcination operations in the ore and mining

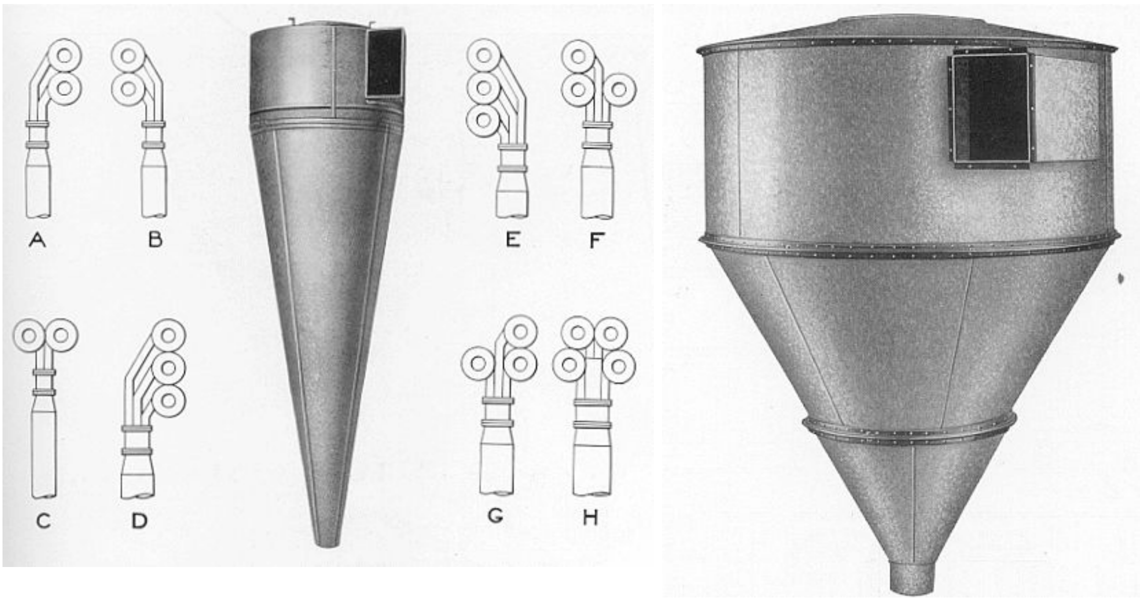


Figure 1.3. Flour mill multi-cyclones manufactured in 1922 by Wolf company [1].

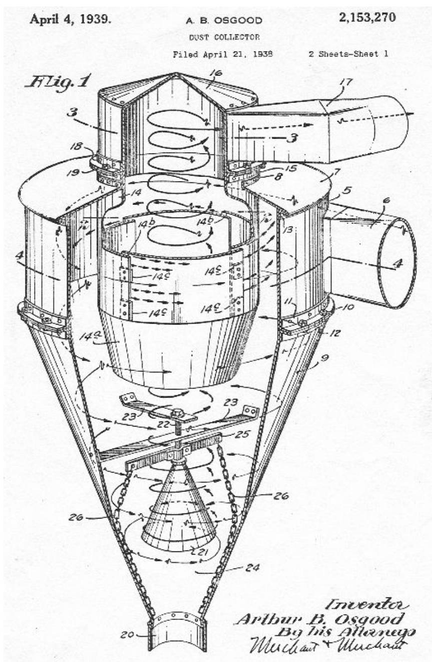


Figure 1.4. Another patent of a cyclone that designed by Osgood in 1939 [1].

Figure 1.5. Some of today's modern cyclones.

plants and chemical industries

- Roasters, rotary kilns, sintering fields, furnaces and converters in the ferrous and nonferrous Metallurgical industries
- Cement plants
- Fluidized bed and reactor riser systems
- Vacuum cleaning machines
- Sand plants and dust sampling equipment
- Incineration field
- Synthetic detergent production units
- Lead, carbon black plants, calcium carbide, Ferro-silicon, expanded perlite
- Chemical plants (plastics, elastomer, polymers, etc.)
- Power generation and refineries

Cyclones have the advantages of classification of solids depending on their characteristics such as, density, mass, shape and size. Likewise, cyclonic separation is used in the structure of process field, especially for separating two-phase fluid type mixtures in an effective manner, for example, heavy hydrocarbons in pipelines or droplets exiting in a venturi scrubber or any other type of scrubbers and separating particles that convey with natural gas in pipelines or many gas pressure drop stations. Despite of the simplicity in construction, they are highly reliable equipment of the many production lines. There are some other examples that include many industries such as removal of water droplets from steam turbines or oil-smog in compressors. There are many researchers and investigators who work on separating particles from fluids, and some of them are pioneers and have valuable improvements in this field, such as Stairmand, Lapple, Eugen Feifel, Koichi Iinoya, Ludwig Leineweber, G. B. Shepherd, Linden, Edgar Muschelknautz, and Walter Barth. All of them worked on fundamentals of the separation and motion in the fluid flow and separation methods in both vertical or horizontal axis. In the 1950s, Barth's theoretical work had a significant effect on research. Many of analysts and scientists followed his theories and formulations as a consequence of the following results continues up to now [1].

The optimization of cyclone performance is one of the major targets of research from many years ago. However, practically catching this high performance is too difficult as a result of the complexity of geometric parameters, especially the collection efficiency related to many factors such as a ratio of input feed, geometrical parameters, fluid flow rates and the condition of the system that cyclone works there.

1.2. Separation of dust from Gas flow

The particles in the air (Floating particles) are clearly the main source of many diseases in the air conditioning systems canals, and generate an actual environmental problem for human and also our modern facilities. Imposing severe restrictions on particle emissions from the processing in industry from governments is one of the main challenges of researchers to find an appropriate method and efficient technology with minimum cost and maintenance with maximum separation of particles and diminishing the defects on the environment and highly advantageous. There are various types of separation apparatus, including bag filters, knock-out drums, electrostatic filters, scrubbers and cyclones that separate dusts and particles for:

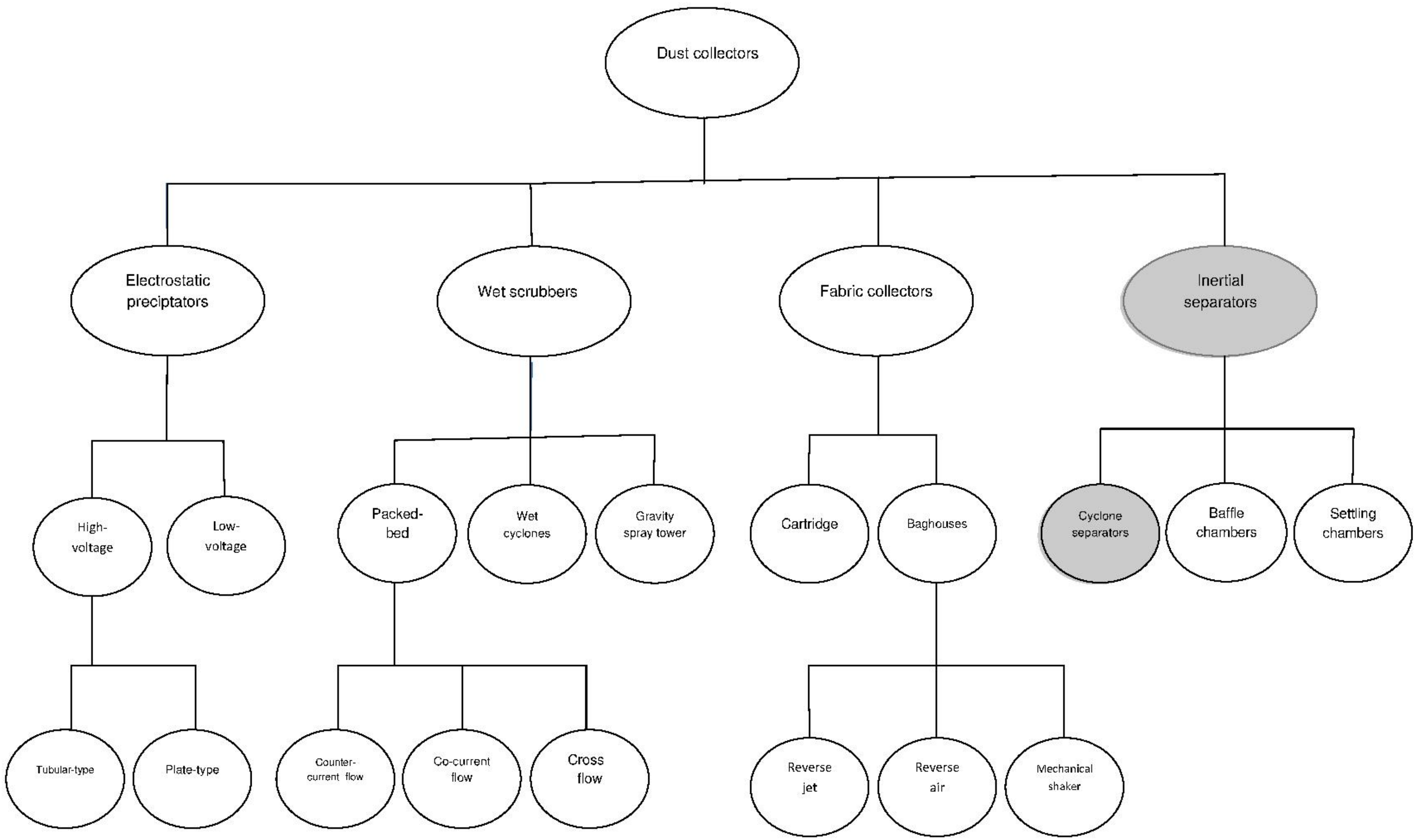


Figure 1.6. Classification of dust collectors.

- Direct sale to customer (elastomer particles of a fluid bed dryer)
- Farther processing (grain processing plants)
- Removing heavy particles or hydrocarbons from process streams
- Using at the process again (e.g. valuable particles)

Another reason for getting rid of process flow particles is to protect downstream equipment, like turbines and blowers, from erosion damage caused by striking particles on the rotor blades or protecting pressure gauges, flow meters and other measuring instruments in gas pipelines. This kind of protection needs investigation of two important criteria: The first one is the maximum diameter of the particles that allow the output gas stream; this is directly related to the devices that we want to protect from impurity, and the second one is the input particle that has different characteristics and specifications such as density, shape, surface charge and erosiveness [1]. Depending on the products and types of particles, classification or separation may be possible with modern separation equipment, including bag filters, cyclones and electro-filters. There are some famous gas cleaning methods with their major pros and cons as mentioned below:

1.2.1. Filtration

Actually, one of the most routine methods for removing fine particles from fluid flow is using filtration techniques. The flow is forced through a filter, which is often made of cloth-like material or paper type, a woven or compressed fibrous. Figure 1.7 illustrates the relative particle sizes with various types, and the appropriate techniques for separating them from fluid [1].

The good performance is the advantage of using filtration. But it has some drawbacks such as pressure drop fluctuation, the material that is worn in the filter, availability and cost of filter cartridges or bags, and indeed, there is not an appropriate way to clean this kind of filter biologically. Hence, in some industry fields such as medicine and food industries, using this kind of filter is impossible. In addition, as a result of material that is used in cloth filters, they cannot work at high-temperature

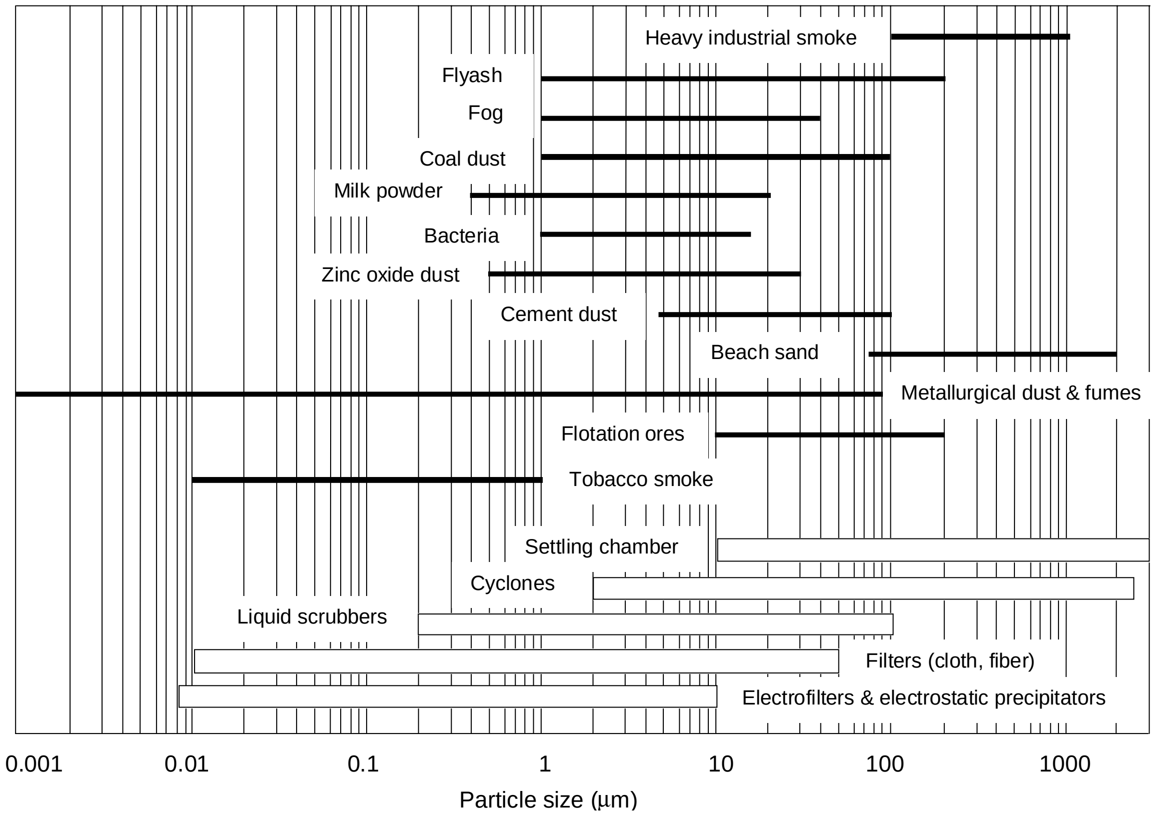


Figure 1.7. Particle size of some materials and recommended methods for removing them from a gas stream [1].

environment, especially over 250 degree Celsius or in any other kind of harsh conditions [1].

Another type of the filter is the electro-filter, occasionally assigned as an electrical or electrostatic precipitator. This device contains two sheets of metal that are charged oppositely and particles that are charged by electricity current as well. One of the benefits of this device is being able to catch the fine particles, especially the particles less than one micrometer in diameter. Furthermore, it can operate in high temperature.

1.2.2. Wet Scrubbers

In this type of filtration, water is sprayed on the input air or in other method, air is passed on water or any kind of liquid, and the result is the same. Hence, the energy of dusts joins together after striking on water droplets, and finally, the particles are separated from the main gas stream. This method is quite effortless and pressure drop of this device is very low, but there are some disadvantages, such as dust particles integrating together and dropping in the main water tank. Ultimately, when considering a wet scrubber, we have to mind that in some cases, the process of particle separation from air causes turning the air pollution problems to a water pollution, but treatment of water is easier than air [1].

1.2.3. Centripetal acceleration and Cyclonic Separation

Cyclonic type of separation based on centrifugal forces are fundamental subjects of this research. Comparing of the other types of separation devices and methods is the main target of this section. The cyclonic separation has advantages and disadvantages as well.

The superiority of these devices are [1]:

- the separated particles and dusts remain dry and, typically reusable.
- so tough and robust structure.
- very compact in size.
- low initial asset and maintenance costs.
- being operated under intense processing conditions, such as, high temperatures and extreme level of pressures and with chemically aggressive environment.
- no moving parts.
- being able to remove neither solids particles or liquid droplets; sometimes in both condition.
- stable pressure drop.
- being fabricated from any available material, including steel plate, casting metals or alloys, plastics, ceramics.
- usage of sticky or tacky solids with convenient liquid irrigation in some of the producing processes.
- being armed with corrosion or erosion resistant or any kind of liners, such as

Teflon. Inner surfaces may be electro-polished to contest against fouling.

Also, some drawbacks of these apparatus are [1]:

- declining performance, when dirty gas is at under low solids-loading, and the result of particle size are under their ”cut size”.
- generally higher pressure loss than other types of separators, in comparison with the low pressure drop scrubbers, bag filters.
- fouling and erosion inner side of cyclone, when inlet dirty gas carries sticky or abrasive materials.
- not being designed and operated appropriately, this device operates below prediction. This problem is common among the other types of separators, especially the fouling and erosion problem which is mentioned above.

1.2.4. Settling Chambers and Knock-out Drums

By using the gravitational effect for the separation of a larger particle of droplets or dust, other devices are used to purify gas stream. The performance of these kinds of devices is better than other separators like cyclones and cotton type filters in larger particles. These filters are typically employed to remove the particles which are greater than about 500 micrometers in size [1].

1.3. Inertial separators-cyclone separators

In this thesis, we will concentrate on cyclonic separation. These kinds of separators works with energy dissipation method using of swirling motion. Dust hits the main body walls. In this case, the particles loose their energy and move down on the walls until they reach the bottom apex by gas stream near the walls. A sketch of a reverse flow with tangential slot type cyclone is shown in Figure 1.8.

In reverse-flow cyclones, the swirling motion is generated using the inlet so-called ”slot.” It helps the dirty gas pushing through the slot into the cyclone tangentially.

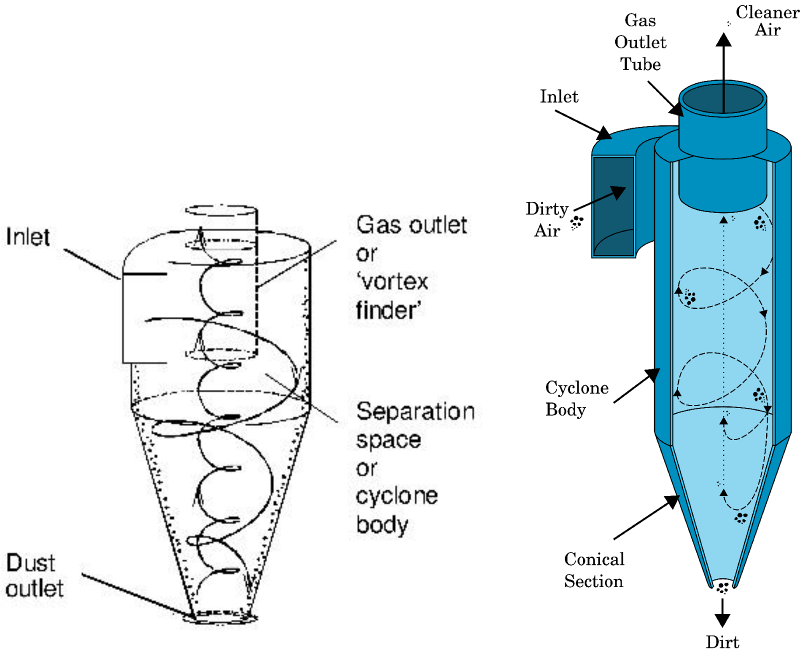


Figure 1.8. Sketch of a reverse flow and conical type cyclone with a tangential slot type inlet [1].

The cross-section of this inlet type is rectangular. As a result of tangential entrance of the gas, the vortex is shaped in the cyclone and goes down through the inner walls of cylindrical part and outer walls of vortex finder. Having touched down to the conical section, the vortex changes its direction and goes upwardly. Finally, the gas will go out through the vortex finder. The geometry of a cyclone with a slot type inlet is determined by the following considerable dimensions:

- Main cylindrical body diameter, **D**
- Overall height of the cyclone, **H**
- Diameter of the vortex finder, $\mathbf{D}_x$
- Length of the vortex finder(inside the cyclone), **S**
- Height and width of the slot, **a** and **b**, respectively
- Height of the conical section, $\mathbf{D}_c$
- Diameter of the dust exit, $\mathbf{D}_d$

Figure 1.9 illustrates the geometry of cyclone. (All dimensions are measured inside the cyclone)

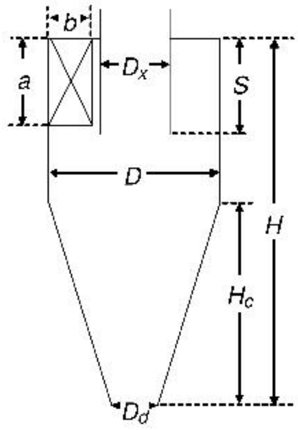


Figure 1.9. The geometrical sizes of cyclone separator.

1.4. Classification of cyclone separators

Classifying centripetal separators according to the following groups:

- The direction of flow input and output of them
- The main body shape
- Their inlet configuration

There are four different types of inlet configurations used in various applications, See Figure 1.10: The first one is the simplest and best known slot-type inlet. These kinds of inlets are normally used in cheap cyclones fabricated from sheet metal or plastic. Many refinery, wood-shop, sand-mill and grain processing units use these kinds of inlets. These types of inlets are manufactured in rectangular-section form. These inlets are generally operated in a big process fields such as petroleum, natural gas and chemical industries. These models have other names such as the rectangular or tangential inlet. Nevertheless, in this thesis, the tangential or slot type cyclone is investigated. Just the number of slots varies. The slot-type inlets are usually very easy to fabricate, and the performance of them is generally satisfactory. According to the fabrication techniques, the starting line of the slot which is placed marginally beneath the top plate of cyclone, is rather at the same elevation as the top plate. This causes an ascending ring of particles that rotate along the upper part in the cyclone. Favorably, the existence of mentioned ring does not affect the cyclonic performance. The second inlet configuration has different names but usually assigned as the wrap-around inlet or Scroll or Volute type inlet. In this sort of inlet, the gas stream is progressively compressed based on the shape of the entrance. Thus, it accelerates upward the fundamental separation space exclusively in cylindrical part. The extraordinary shape of this type of inlet causes a perfect phenomenon to establish a great angular momentum in the root of spin. This just happens as a result of radius differences in inlet area. As the shape of this inlet is more massive than the other types, this cyclone has a bigger vortex finder in diameter. Likewise, this form of the inlet is extensively operated in high solid loading processes, especially highly fraction particles. Figure 1.10, illustrates an entire form of the wrap-around scroll with 360 degrees. Indeed, 180 and 270 degrees of scrolls are frequently used, and they are more compact and simpler to use [1].

The third inlet design is 'Helical roof'. In this type of inlet, as a result of ring shape design around the vortex finder, the flow stream does not hit the vortex finder directly.

The fourth group of the inlet is swirl vanes. As shown in the figure, this type of inlet form leads the air stream into the cyclone with parallel vanes that positioned axially on the cyclone. These vanes are seated between the vortex finder and main body of cyclone. Swirl tubes are usually in small in size and are typically set inside the pressure vessels [1].

In summary, two main groups of devices that mostly operated in many industries and some laboratories have been introduced. They are mainly reverse flow sort:

- Cyclones: a device with slot type inlet, cylindrical body, and with/without cone
- Swirl tubes: a device with axially inlet from top, swirl vanes, and the main body is cylinder

In this thesis, slot type and tangential inlet cyclone are studied. It should be mentioned that from the context in each case, whether the designation 'cyclone' refers

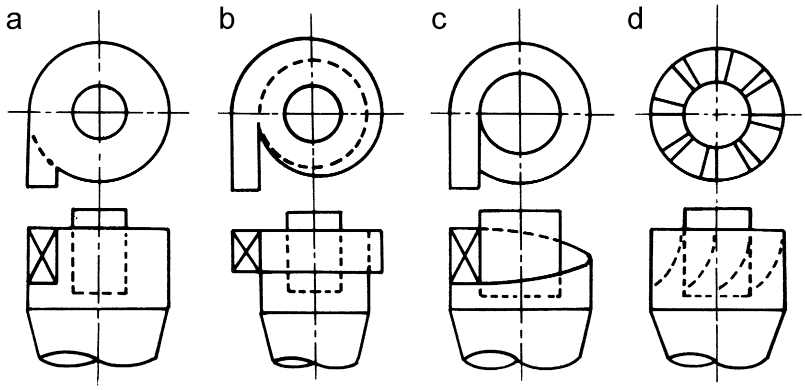


Figure 1.10. Side and top views of the four well-known inlet configurations. a 'slot' (also called 'tangential') inlet, b 'wrap-around' inlet, c 'helical roof' inlet and d axial inlet with swirl vanes [1].

to centrifugal separators in general, by using cone shape that is jointed to the cylindrical part. These are referring to the special type of cyclonic separator with extensive usage in many industries such as oil, natural gas and Calcination processes.

1.5. Literature Review

The most important parameter that affects the cyclone performance and flow pattern is the cyclone geometry. For reversed flow cyclones, there are seven main geometrical parameters. The inlet height **a**, the inlet width **b**, the vortex finder diameter $\mathbf{D}_x$, the vortex finder length **S**, the cyclone total height **H**, and the cone-tip diameter $\mathbf{D}_d$. These dimensions can be expressed in terms of barrel diameter **D**. Two performance indexes are the pressure drop and the efficiency of particle separation. For low mass loading cyclone separators, the cut-off diameter $\mathbf{x}_{50}$ is usually given instead of grade efficiency curves. ($\mathbf{x}_{50}$ will be discussed in the next chapter.)

1.5.1. Study approaches

There are many researchers focused on the effect of cyclone geometry on performance.One or more of the three main approaches of study are used by researchers. These approaches are:

- Analytical methods (mathematical models), which can be classified into [3]:
  - (i) Semi-empirical and theoretical models
  - (ii) statistical models
- Experimental measurements
- Computational fluid dynamics (CFD) simulations

Recently, optimization studies based on data obtained from one of the approaches have been performed.

1.5.2. Mathematical models

The theoretical models were developed by many researchers such as, Alexander [4], Shepherd and Lapple [5], First [6], Zhao [7], Stairmand [8], Barth [9], Avci and Karagoz [10, 11] and Chen and Shi [12]. These models were derived from mathematical relations and physical characterizations. They worked on the characteristic of gas flow pattern in the cyclone and most importantly the focused on energy dissipation. Furthermore, as a result of some initial assumptions and simplifying some boundary conditions in theoretical models, significant differences in predicted models and measured results are observed. Sometimes the results are two times larger than the empirical outcomes [13]. Since the first application of gas type cyclones in 1886 [14], theories for the estimation of both particle collection efficiency and pressure drop of cyclone have been done by many researchers and investigators by testing various methods and simplification of initial hypotheses in the last fifty years. Many studies focused on pressure drop and collection efficiency of cyclones [15]. The most widely used mathematical models for the pressure drop and cut-off diameter estimation are:

- Shepherd and Lapple model [5]
- Stairmand model [16]
- Barth model [9]
- Rietema model [17]

- The Muschelknautz method of modeling (MM) [1, 18–22]
- Casal and Martinez-Bent model [23]
- Iozia and Leith model [24]
- Ramachandran model [25]

1.5.3. Computational fluid dynamics (CFD) modeling

Boysan et al. [26] investigated the cyclone separator based on the CFD outputs. Hence, this approach is widely used to simulate the flow and to evaluate the cyclonic collection efficiency. Similarly, Griffiths and Boysan [27] explored three different cyclones, computationally. They measured the initial pressure losses using the CFD outputs and their results were so close to the outcomes of experimental data measured based on the real test. This technique of the modeling is able to forecast the aspects of cyclonic separation details, which contributes an appropriate model of flow field in cyclone [27]. Therefore, CFD technique is a reliable and cheap way of exploring the effect of different design parameters on the performance of cyclone. Furthermore, this makes CFD technique superior to experimental techniques, because the cost of CFD approach is very lower than experiments in the laboratories, especially in geometrical optimization. In other words, CFD method decreases the cost of optimization. Gimbun et al. [28] implemented CFD to investigate inlet velocity and temperature variation on the pressure loss in the cyclone [3]. This research has been done by many investigators, for instance [2, 28–35]. Nevertheless, by comparing with CFD and mathematical techniques, we can realize that the CFD method is still an expensive method. There are some crucial outcomes that cause an increase in the price of the CFD in comparison with mathematic approaches. They are :

(i) In basis, the CFD process requires interference by an expert researcher at every stage (geometry drawing, mesh generation, boundary conditions, setting solvers and post processing).

(ii) The license charge of the software is too high.

(iii) The running cost exclusively for unstable and turbulent simulations which require parallel processing.

(iv) The results often require validation with experimental outcomes and achieve the same results based on the various meshing methods to catch correct outputs independently from grids.

1.5.4. Reviewing of previous studies

In this section, the effects of the geometrical parameters on the performance in terms of the two indicators; the pressure drop and the separation efficiency will be discussed briefly based on the literatures. More details will be discussed in the subsequent chapters.

(i) The cone tip diameter

- Some information and documents are available about changing the dimension of cone tip cyclones when the other geometrical parameters are constant such as [36]. Bryant et al. [37] worked on this section of cyclone and when the air vortex comes down to the cone part sometimes the shape of the cone causes a phenomenon that is called re-entrainment. This causes the return of some particles to the middle vortex and comes out from cyclone and performance of the cyclone will be deteriorated. Thus, particle collection will be reduced for cyclones that have a narrow cone tip. Based on study done by Xiang et al. [36], the cone size is not a crucial section for the operation of cyclone, although it works as a function of guiding particles that are separated from the main vortex. Nevertheless, the investigation of Lee and Zhu [38] on cone tip demonstrated that the shape of the cone established a tangential velocity near under flow part before getting rid of tiny particles. Some of the earlier studies indicated that cone tip diameter has a trivial effect on the overall efficiency. However, by reducing the diameter of this part, tangential velocity rises gradually, but the placement of it is constant [39].

(ii) The underflow sealing geometry

- The design, operation and working condition of the underflow configuration can chiefly affect the cyclone collection efficiency. Indeed, the performance of cyclone is just as good as its underflow design. According to the observation of earlier researchers, about 90 percent of all related cyclone problems are due to issue associated with the failure of the collected particles [1]. Typical cyclones always have a dustbin part attached to the end of the bottom apex to gather the separated solid particles. While a gas flow enters the dustbin with close end, some parts of the flow turn back into cyclonic process, and causes some disturbance inside the cone part and as mentioned before the name of this abnormality is re-entrainment and it causes reduction in the performance of the cyclone [40]. There are some other investigations about dust geometries such as [41–44]. Obermair et al. [44] focused on the experimental methods on the dustbin geometry, and also they monitored some disturbances in this part. The consequence of these tests proves that the performance of the cyclone would be enhanced extremely by changing the dimensions in this part and also they continued their studies about this matter to clear up the influence of dustbin in collection efficiency. There is another part that can be used as a dustbin called dig-leg which is like a vortex finder but installed in the bottom apex. There are some studies on this part such as [43, 45]. Lee and Xiang [35] observed that the jointed part had to be integrated based on the flow stream and the working condition of the cyclone. However, there are various investigations without considering this part in their experiments [e.g., [46, 47]].

(iii) The inlet dimensions

- According to the researchers and investigators on the influence of inlet dimension on the outcomes of cyclonic separation, it is observed that the collection efficiency, cut size diameter and other designing criteria are altered by changing of the natural length or vortex length of the main spin. One of these researchers is Alexander [4]. As mentioned before, the reverse type cyclones have two vortex motions in the cyclone body: the inner and outer spiral. These vortexes directly make a relation between the inlet dimensions and an axial distance called L_n. This length starts from the place of switching the direction of spin up to the vortex finder. [18]. The length has some other names that are "turning length", "natural length" or "vortex length." One of the researchers [4] discovered that L_n is the ratio of the input area and it is diminished, but still there is some contradictory tendencies about this relation [18]. Also, there are some other studies which have observed the influence of the inlet geometry changing and efficiency of cyclone, there are [28, 36, 48–50]. However, all of them reported these relations, but they have not mentioned the consequence of this investigation in detail, especially when some of them use different sorts of inlet or increasing the number of slots in a cyclone. They have just illustrated some velocity patterns and pressure loss in their reports. Adding a second or third slot is one of the new approaches that is considered in some researches, [51, 52]. There is another work about inlet dimensions using Reynolds stress model (RSM) [2]. The research has investigated that when the inlet height and the inlet width increases, the tangential velocity decreases. Furthermore, they compared the change in the inlet height and width with pressure loss inside the cyclone. They have an inverse relation [2]. But, he has not mentioned the results of this research in detail.

(iv) The vortex finder dimensions

- The geometry of the vortex finder is one of the crucial dimensions in the cyclone.It significantly influences the separation efficiency as its size performs a critical role in representing the flow field inside of the cyclones. Hochstrasser and Saltzman [53] researched the performance and design of mini cyclone for repairable aerosol sampling; each of them has different clean gas outlet diameter. Leith and Iozia [24] enhanced the collection efficiency of the cyclones according to their developed program which just focused on the vortex finder variation. Lee and Kim [54] sought for a relation between the diameter of main body **D** and vortex finder D_x and influence of them on the pressure drop and performance. Mcfarland and Moore [55] analyzed some samples with different vortex finder diameters and investigated the influence of changing D_x with cut size diameter when the Reynolds number is constant. Recently, Hoekstra [56] investigated the effect of outlet diameter on the velocity profile using 2-D axi-symmetric simulations. Lim et al. [49] examined the effect of the vortex finder shape on the collection efficiency at different flow rates experimentally but without any explanation on its effect of the flow field pattern and velocity profiles. Raoufi et al. [50] duplicated the same study of Lim et al. [49] numerically but the detail of their research is very limited. Lacor et al. [57] simulated nine cyclones with different vortex finder dimensions (diameter and length) by using the Large Eddy Simulation (LES) methodology, to declare the influence of changing the dimension of vortex finder with efficiency and flow stream. Their results showed that when D_x increases, the maximum tangential velocity decreases. However, increasing the vortex finder length makes a small change in both the static pressure, axial and tangential velocity profiles.

(v) The cyclone heights

- Limited literature is available for the effect of cyclone height. Zhu and Lee [38] worked on the cyclone's height based on experimental outcomes, and their results declared that there is a direct relation between increasing the height and collection performance. Nevertheless, they did not prepare any consequence of their works on the flow pattern or even explanation for the efficiency results. Hoffmann et al. [58] reported that cyclone performance increases when the coefficient of cyclone overall length and main body diameter is up to 5.5 But if this size is larger than 5.5, the performance of the cyclone will decrease dramatically. However, they did not present any contour plot or velocity profile to assist the explanation for the effects of cyclone height on performance. Recently, Xiang and Lee [35] have repeated the same study of Zhu and Lee [38] for the effect of cyclone height computationally via steady three-dimensional simulation using Reynolds stress turbulence model (RSM). They found that the tangential velocity decreases by increasing cyclone height, which is responsible for the lower separation efficiency observed in long cyclones. The explanation of this behavior was not adequate. Moreover, no particle tracking study was presented. Elsayed et al. [42] modeled six different overall height of cyclones by using the Reynolds Stress Model (RSM) to discover any relation between this height and efficiency of cyclones. The results deployed that when overall height increases, the tangential velocity decreases and there is not any acceleration inside the cyclone. Meanwhile, growing the barrel height makes a small change in the axial velocity.

2. MODELING AND PARAMETERIZATION

Over a prolonged duration of more than 30 years, Professor Edgar Muschelknautz, with his colleagues and students have evolved the most feasible way to design cyclonic separation up to now. The origins of Muschelknautz method (MM) comes from the initial idea by Professor W. Barth of the University of Karlsruhe. Throughout the years, in the act of considering the fundamental phenomenon and measuring techniques expanded by Muschelknautz and co-workers, have progressed to clarify the model. In this chapter, we will present the features of MM that help us to evaluate an appropriate design in the cyclonic separation field.

The final revised Muschelknautz method manifests three essential features [1]:

- The capability to calculate the effects of wall roughness to get to materials physical roughness.
- The capability to calculate the effects of solids saltation or mass loading.
- The capability to calculate the influence of particle size distribution (PSD) of dirty gas with the main body geometries variation.

Since 1886, so many cyclone models have been developed by using different methods of evaluation for optimization of the design parameters and performance. As mentioned before, cyclone exists under different structures but the reverse flow cyclone is the most common one in industry. Moreover, in this thesis slot type, tangential inlet will be investigated, and the main focus will be on the number of slots for each model of cyclone. In addition, main cyclone body dimension is $50mm$ about 2 inches and inlet is the tangential rectangular type.

There are two main categories that will be challenged. In first category the four well-known models of cyclone separators. Those models were Muschelknautz D type, Stairmand high efficiency, Lapple general purpose and Swift high efficiency. The next step is redesigning a model of cyclone separator that is produced by one of the famous

European manufacturers. In this model just inlet length and width and vortex finder length will be changed, and the results will be compared with original geometry.

2.1. Functions and Formulation of Muschelknautz Method

In this part of the study, we will present the required formulation to design, evaluate and calculate a regular reversed flow cyclone separator with cone type based on the final Muschelknautz methods (1990-1992). Apparently, some formulas have been modified during an empirical experiences and preferences of researchers such as Trefz and Hoffmann during last 10 years.

Initially, The cyclone separator performance and the flow field are affected mainly by the cyclone geometry where there are seven main geometrical parameters, namely, the inlet height **a** and width **b**, the vortex finder diameter $\mathbf{D}_x$ and length **S**, the barrel height **h**, the cyclone total height **H** and the cone-tip diameter $\mathbf{D}_c$. All of these parameters are always expressed as a ratio of cyclone body diameter **D**. In this thesis, just the influence of geometry variation will be investigated. All dimensions, elevation views and placements of velocities are illustrated in Figures 2.1 and 2.2.

The first formulation of MM starts to calculate the entrance 'constriction coefficient' α for a typical slot type with tangential input from the experimental formulation:

$$\alpha = \frac{1}{\xi}\left\{1 - \sqrt{1 + 4\left[(\tfrac{\xi}{2})^2 - \tfrac{\xi}{2}\right]\sqrt{1 - \tfrac{(1-\xi^2)(2\xi-\xi^2)}{1+c_o}}}\right\} \tag{2.1}$$

where $\xi = b/(1/2D) = b/R$ (D represented the main cyclone body diameter) and c_o is the proportion of the mass of solids in dirty gas flow to mass of input gas in the stream feeding flow.

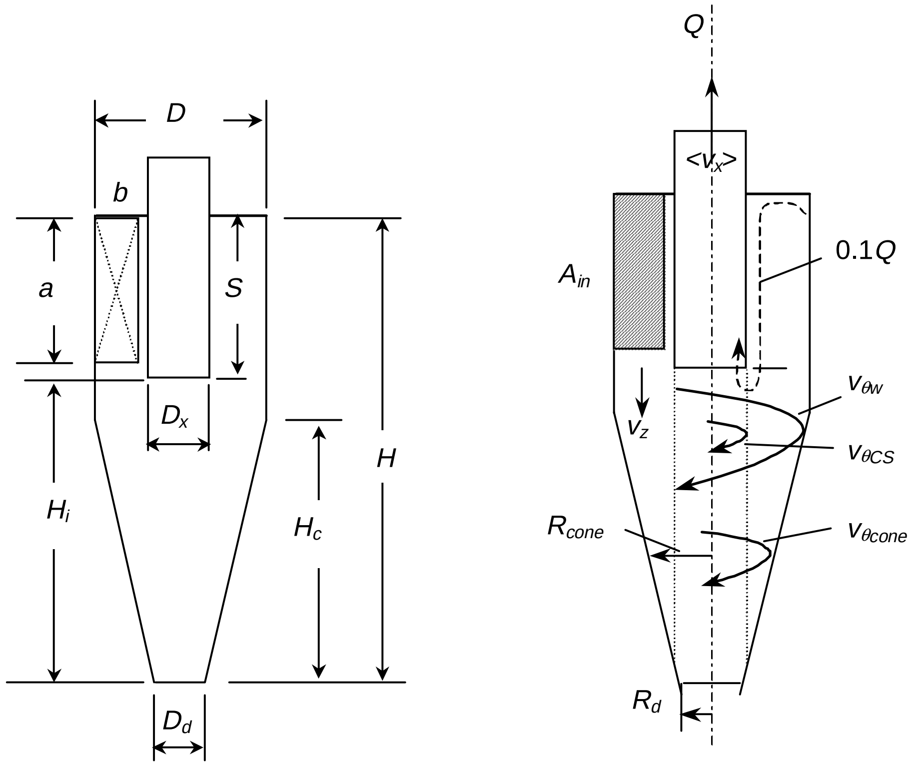


Figure 2.1. Dimensional notation and placements of velocities inside the ordinary cyclone with cone type [1].

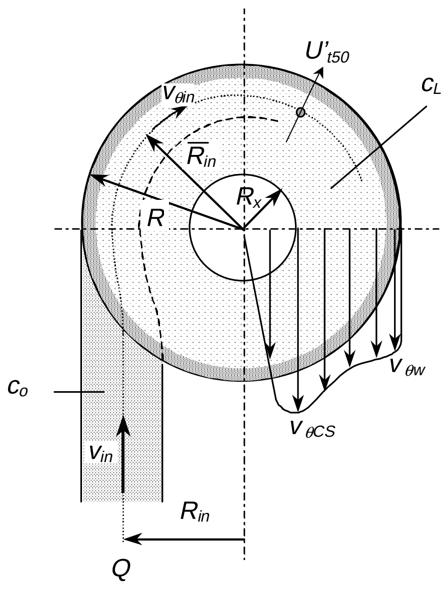


Figure 2.2. Upper section of conventional cone type cyclone with further more information about velocities and dimensions [1].

After calculating α, other components can be evaluated by using below formulas:

- the Input velocity can be calculated as shown below:

$$v_{in} = \frac{Q}{A_{in}} = \frac{Q}{ab} \tag{2.2}$$

- the Wall velocity, $v_{\theta\omega}$, is then,

$$v_{\theta\omega} = \frac{v_{in} R_{in}}{\alpha R}, \tag{2.3}$$

- the Geometric Mean Radius:

$$R_m = \sqrt{R_x R}, \tag{2.4}$$

- the Wall Axial velocity:

$$v_{z\omega} = \frac{0.9Q}{\pi(R^2 - R_m^2)}. \tag{2.5}$$

Trefz and Muschelknautz experimentally discovered that approximately 10 % of input flow of gas directly goes out without establishing a vortex in the cyclone. This is a kind of leakage or so-called short circuits, as illustrated in Figure 2.1. According to their study, the boundary layer flow can fluctuate from about 4 % to 16 % of inlet flow rate. Nevertheless, in many studies assumed that an appropriate amount of flow rare (Q) is 10 %. Consequently, about 90 % of the incoming gas directly contributes in the flow along the walls and in the formation of the inner vortex. As empirical data will show, the inner vortex flow has a significant influence on the cut-Size diameter, x_{50} [1]. x_{50} is the particle size that stands a 50-50 chance of being captured.

- the total inside area of the cyclone contributing to fractional drag:

$$\begin{aligned} A_R &= A_{roof} + A_{barrel} + A_{conc} + A_{vt} \\ &= \pi \left[R^2 - R_x^2 + 2R(H - H_c) + (R + R_d)\sqrt{H_c^2 + (R - R_d)^2} + 2R_x S \right] \end{aligned} \quad (2.6)$$

- the Froude number:

$$Fr_x = \frac{v_x}{\sqrt{2R_x g}} \quad (2.7)$$

where v_x is the superficial axial velocity through the cross section area of the vortex finder.

- the Friction Factor:

For calculating the friction factor, we first calculate the gas-phase wall friction factor, f_{air}. It is the sum of two main friction components, which are smooth wall friction, f_{sm}, and the wall roughness friction, f_r. These formulas are just used for conical-body cyclones. (k_s represents wall roughness and $r_a = R$)

$$f_{air} = f_{sm} + f_r \quad (2.8)$$

$$f_{sm} = 0.323 Re_R^{-0.623} \quad (2.9)$$

$$f_r = \left(\log(\frac{1.60}{\frac{k_s}{r_a} - 0.000599})^{2.38}\right)^{-2} \left(1 + \frac{2.25 * 10^5}{Re_R^2(\frac{k_s}{r_a} - 0.000599)^{0.213}}\right)^{-1} \tag{2.10}$$

then, for computing the total gas-plus-solids wall, the friction factor can be expressed as:

$$f = f_{air} + 0.25(\frac{R}{R_x})^{-0.625}\sqrt{\frac{\eta c_o Fr_x \rho}{\rho_{str}}} \tag{2.11}$$

The ρ_{str} term, which represents the Bulk density of the particles is about equivalent to $0.3\rho_{bulk}$ to $0.5\rho_{bulk}$, where ρ_{bulk} is the Bulk density of input solids at rest. In this study, the amount of bulk density assumed $0.4\rho_{bulk}$, and the ρ_{bulk} is half of the input particle density.

- the Inner Core velocity:

$$v_{\theta CS} = v_{\theta\omega}\frac{(R/R_x)}{\left[1 + \frac{fA_R v_{\theta\omega}\sqrt{R/R_x}}{2Q}\right]} \tag{2.12}$$

- the Mean Rotational velocity:

$$v_{\Theta m} = \sqrt{v_{\Theta w} v_{\Theta CS}} \tag{2.13}$$

$v_{\Theta m}$ is a geometrical mean rotational velocity based on the vortex velocity near the wall, $v_{\Theta w}$, and the velocity in the inner vortex in control surface region, $v_{\Theta CS}$.

- the Cyclone Body Reynolds number:

$$Re_R = \frac{R_{in} R_m v_{z\omega} \rho}{H\mu(1 + (v_{z\omega}/v_{\theta m})^2)} \tag{2.14}$$

In above equation , μ and ρ represent the gas phase absolute viscosity and density, respectively.

- the Terminal velocity of the cut-size particle rotating in Control Surface (CS):

$$U_{t50}^{'} = v_{rCS} = \frac{Q}{2\pi R_x H_{CS}} \tag{2.15}$$

- the Particle Reynolds number:

$$Re_p = \frac{\rho U_{t50}^{'} x_{50}}{\mu} \tag{2.16}$$

- the Cut-Point size:

  Cut-point diameter or cut-size, x_{50}, plays a crucial role in the cyclone. This size of particle has a 50% probability to be captured. It is a measure of the intrinsic separation capability of the cyclone.

  If $Re_p <\sim 0.5$,

$$x_{50} = 5.18 \frac{\mu^{0.375} \rho^{0.25} U_{t50}^{'0.875}}{(\frac{(\rho_p - \rho) v_{\Theta CS}^2}{R_x})^{0.625}} \tag{2.17}$$

But, if the upper condition does not cover, the cut-size dimension is expressed as:

$$x_{50} = x_{fact} \sqrt{\frac{18\mu(0.9Q)}{2\pi(\rho_p - \rho) v_{\theta CS}^2 (H - S)}} \tag{2.18}$$

This equation is a variation of Barth formulation. The amount of x_{fact} is assumed

1. This term is a correction factor, and it will be varied between 0.9 to 1.4. However, in the normal condition, many researchers assume 1 for simplicity.

- the Drag Coefficient:
  valid for $0.3 < Re_p < 1000$

$$C_D = \frac{18.5}{Re_p^{0.6}} \tag{2.19}$$

- Collection Efficiency and Performance:
  The grade efficiency curve η is typically integrated with two main parameters; the cut size diameter, x_{50}, and the coefficient of a grade efficiency slop, m. In other words; this equation is a function of $\eta(x_{50}, m)$. The amount of m is varied between 2 to 7 for particular grade efficiency formula. In the early stage of designing a new cyclone separator, if there is not any grade efficiency data, it is better to choose an appropriate slope according to the experimental results with a similar design specification, especially alike geometry and operation environment. According to the articles on cyclonic separation, for typical cyclones, the slop is about 3 and for well-designed and smooth walled cyclones is about 4-6 [1]. In this thesis, the amount of m is assumed 5. For calculation of grade efficiency based on the particle size, Equation (2.20) is used.

$$\eta_i = \frac{1}{1 + \left(\frac{x_{50}}{x_i}\right)^m} \tag{2.20}$$

For evaluation of overall collection efficiency, the feed size fractions (N) should be known. Multiplication of grade efficiencies and sum of all N fractions give us the overall collection efficiency, according to Equation (2.21).

$$\eta = \sum_{i=1}^{N} \eta_i \times \Delta MF_i \tag{2.21}$$

where ΔMF_i is the i^{th} mass fraction.

- Mass Loading:

  Determining the mass loading (saltation) effect is one of the important parts of designing the cyclone separator. Based on the Muschelknautz method, the range of particles inside the inlet air, has a relation between cut size, solid loading and median size of particles [1]. The equations are shown as below:

$$c_{oL} = 0.025(\frac{x_{50}}{x_{med}})(10c_o)^{0.15},\ for c_o \geq 0.1 \tag{2.22}$$

or

$$c_{oL} = 0.025(\frac{x_{50}}{x_{med}})(10c_o)^{k}, for c_o < 0.1 \tag{2.23}$$

where,

$$k = -0.11 - 0.10 \ln c_o \tag{2.24}$$

  Furthermore, if $c_o < c_{oL}$, then the mass loading (saltation) does not happen during entrance of flow into the cyclone. This phenomenon is known low solid loading. It means a fine feed particle distribution and a large cut-point diameter. There is another point of view, which is high solid loading or saltation factor. This phenomenon will occur, when $c_o > c_{oL}$. In this condition, the cyclone will turn into a double step separator: the weight fraction of incoming solid particles exceeding the limit loading will be forced to the walls immediately during entrance. The fraction that stands in turbulent suspension will be exposed to separation in the inner spin based on the particle size distribution [1].

- Pressure Drop:

There is a direct relation between effect of solid loading and pressure drop in the cyclone separator. According to the MM results, the reason came back to friction between solids with the wall and irreversible losses within the vortex core, and sometimes inlet acceleration takes place inside the cyclone. The Wall Loss, or the loss in the cyclone body, is calculated by using below Equation:

$$\Delta p_{body} = \frac{f A_R \rho (v_{\Theta w} v_{\Theta CS})^{1.5}}{1.8Q} \tag{2.25}$$

The Loss in the vortex finder and the core region is given by,

$$\Delta p_x = \left[2 + \left(\frac{v_{\Theta CS}}{v_x} \right)^2 + 3 \left(\frac{v_{\Theta CS}}{v_x} \right)^{\frac{4}{3}} \frac{1}{2} \rho v_x^2 \right] \tag{2.26}$$

In some places that we install the cyclone, the input gas-solid mixture should be accelerated from a low velocity region which exists at the cyclone inlet. To apply the mechanical energy balance between a point in the high and low velocity regions, acceleration pressure loss should be evaluated in the cyclone.

$$\Delta p_{acc} = (1 + c_o) \frac{\rho (v_2^2 - v_1^2)}{2} \tag{2.27}$$

where $(1 + c_o)\rho$ is the density of the gas-solid mixture undergoing acceleration from upstream velocity v_1 to downstream velocity v_2. Most of the time, this part is negligible.

Finally, the total pressure loss is the summation of the wall, vortex finder and the acceleration loss.

$$\Delta p = \Delta p_{body} + \Delta p_x + \Delta p_{acc} \tag{2.28}$$

The Equations (2.1)-(2.28) were taken from Muschelknautz method that explained at the Gas Cyclones and Swirl Tubes book - chapter 6 [1].

2.2. Applied Boundary Conditions

There are some boundary conditions and initial conditions, which applied to the models in MM and COMSOL [59]. They allow us to catch feasible results and to gain a well arrangement of simplification and scientific assumption in our initial conditions and results, simultaneously. They are:

- The particles are assumed as spherical-shaped.
- The particle motion is not influenced by the presence of neighboring particles interaction.
- The radial velocity of the gas is negligible and it can be equal to zero.
- Input velocities are 2 m/s and 10 m/s.
- Feed particle sizes are 2, 4, 6 and 8 μm.
- Feed particle numbers are 100 for each size.
- The upper part of the vortex finder (top lid) and bottom apex (underflow lid) are open.
- In the COMSOL, inlet velocity for laminar flow is 2 m/s and for turbulent flow (RANS) is 10 m/s.
- The weight fractions of particles are 0.25, 0.5, 0.75 and 1.
- Density of air is 1.225 kg/m^3.
- Critical temperature and pressure of air are -140.5 degree Celsius, and 37.71 bar at 15 degree Celsius, respectively.
- All main body diameters are 50 mm (about 2 inches) (D).
- The particle tracing for fluid flow module in COMSOL is integrated with laminar and turbulent modules for low and high velocity inlets.
- The particle's density is 2730 kg/m^3.
- The geometrical dimensions are in Tables 3.1 and 3.6.

3. RESULTS AND DISCUSSION

This thesis considers four well known models, namely, Muschelknautz D type, Stairmand high efficiency, Lapple general efficiency and Swift high efficiency. There is another model, so called SS model, in which all geometrical parameters are fixed except **a**, **b** and **S**. Mathematical evaluation (based on Muschelknautz method of modeling (MM)) and computational fluid dynamics (by using COMSOL) are the important methods to understand the influence of geometrical differences on cyclone performance and cyclonic separation. Some of the significant geometrical parameters are: The vortex finder diameter, Inlet section width, Inlet section height and Cyclone total height.

The effects of both the barrel height and the vortex finder length on the cyclone separator performance are negligible in comparison to other parameters. There are strong interactions between the effects of inlet dimensions and the vortex finder diameter on the cyclone performance. Therefore, in the first case study, we compared four well known models with different geometries. All four models have the same body dimension size. In the second case study we focused on the effects of using different inlet dimensions and finding a right size to boost collection efficiency of cyclone in single or double input.

The effect of inlet section dimensions on the cyclone performance has caught the interest of researchers and there is a wide range of scientific literature that related to this subject. According to their results, this part of cyclone has a significant effect on the separation efficiency and pressure drop. In other words, this variation of inlet section causes a phenomenon known as natural length (or vortex length), that studied by Alexander [4]. Cyclones have two vortex motions; outer and inner. In the reverse flow cyclone, the gas flow after entrancing into the cyclone changes its direction between vortex finder and the main body walls and establishes an outer spin. Usually that gap between vortex finder and the main body walls has some specific names such as the turning length, natural length or vortex length of the cyclone [48, 50, 60, 61]. Although there are many studies on the influence of geometrical specifications on the performance and flow streams, their results are still not clear. In the second case study, we will concentrate on the inlet area, which is one of controversial subjects nowadays [49, 51, 62].

3.1. FIRST CASE STUDY: FOUR WELL-KNOWN MODELS

The purpose of this study is to compare four well-known models by focusing on average output velocity, Reynolds number, and separated particles based on COMSOL and Mathematical outputs. The main goal of this part is to illustrate the performance of these cyclones. Table 3.1 summarizes the geometrical parameters.

Table 3.1. Geometric dimensions of four famous models.

	a	b	S	D_x	D_d	H	H_c
Muschelknautz-D type	0.52D	0.15D	0.89D	0.33D	0.55D	2.42D	1.68D
Stairmand High Efficiency	0.5D	0.2D	0.5D	0.5D	0.38D	4D	2.5D
Lapple General Purpose	0.5D	0.25D	0.63D	0.5D	0.25D	4D	2D
Swift High Efficiency	0.44D	0.21D	0.5D	0.4D	0.4D	3.9D	2.5D

Two types of cyclones with the same geometries and different number of slots (single slot or double slot) are considered. Single slot cyclones data set shown in Table 3.2 are chosen to be the average magnitude velocity (m/s) and average Reynolds number of clean gas in the output section of the vortex finder. Meanwhile, similarly Table 3.3 represents the double input cyclones that expose the velocity and Reynolds number in laminar and turbulent solvers with the same inputs and boundary conditions with single slot. (The average velocity unit in the clean gas side is meter per second.)

Table 3.2. Single slot input-COMSOL's results.

	V-Laminar	V-Turbulent	Re-Laminar	Re-Turbulent
Muschelknautz-D type	0.40496	1.59974	7.3297	26.39658
Stairmand High Efficiency	0.70237	3.36402	16.84951	73.7674
Lapple General Purpose	1.28529	6.36031	31.13984	144.14554
Swift High Efficiency	0.72393	3.48198	16.58235	72.86426

According to the information in the tables, average velocity and Reynolds number

Table 3.3. Double slot inputs-COMSOL's results.

	V-Laminar	V-Turbulent	Re-Laminar	Re-Turbulent
Muschelknautz-D type	0.96756	3.64912	20.37086	72.20817
Stairmand High Efficiency	1.6035	8.40758	37.0945	178.67177
Lapple General Purpose	2.66339	13.41476	64.07802	308.80939
Swift High Efficiency	1.70972	8.90594	37.07794	178.15374

decrease when the cyclone is chosen as a single slot. Even though each model has unique dimension ratios, velocity and Reynolds profiles are completely different.

Moreover, there are different types of mathematical methods to design the cyclone separator. In this thesis, the Muschelknautz method formulation that has been mentioned in the previous chapter (just for single slot cyclones) has been used. The results of these functions are indicated in Tables 3.4 and 3.5 for different input velocities. Figures 2.1 and 2.2 illustrate the placement of velocities inside the cyclone. The following items depict the parameters that are used in the tables and that have been extracted from Muschelknautz method.

- Wall velocity, $V_{\Theta\omega}$
- Wall axial velocity, $V_{Z\omega}$
- Tangential velocity of gas at the inner core, $V_{\Theta CS}$
- Cyclone body Reynolds number, Re_R
- Particle Reynolds number, Re_P
- Froude number, Fr_x
- Total wall area of the cyclone separation space, A_R
- Cut size diameter, x_{50}
- Drag coefficient, just valid for $0.3 < Re_P < 1000$, C_D

Table 3.4. Single slot- Vin=2 m/s -MM's results.

	Units	Muschelknautz-D type	Stairmand High Efficiency	Lapple General Purpose	Swift High Efficiency
Normal vol. flowrate	Nm^3/h	2.48	3.1	3.8	2.82
$V_{\Theta\omega}$	m/s	2.44	2.57	2.59	2.597
$V_{Z\omega}$	m/s	0.25	0.419	0.513	0.317
$V_{\Theta CS}$	m/s	1.58	1.209	1.47	1.089
Re_R	-	41.8	47.2	53.6	33.06
Re_P	-	0.0038	0.0025	0.0023	0.0028
Fr_x	-	4.25	1.88	2.3	2.98
A_R	m^2	0.0202	0.0289	0.0296	0.0281
X_{50}	m	4.69e-6	4.096e-6	3.49e-6	4.89e-6
C_D	-	521.48	675.14	705.69	627.22
Total pressure drop	Pa	18.74	10.79	13.14	13.04
Solid loading	-	high	high	low	high
Co	kg/kg	8.16e-6	6.93e-5	1.306e-4	2.61e-6
Efficiency	per cent	92.18	65.1	45.62	75.98

Table 3.5. Single slot- Vin=10 m/s -MM's results.

	Units	Muschelknautz-D type	Stairmand High Efficiency	Lapple General Purpose	Swift High Efficiency
Normal vol. flowrate	Nm^3/h	12.41	15.5	18.93	14.07
$V_{\Theta\omega}$	m/s	12.24	12.88	12.93	12.95
$V_{Z\omega}$	m/s	1.25	2.09	2.55	1.58
$V_{\Theta CS}$	m/s	15.11	11.04	12.38	11.15
Re_R	-	210.77	241.89	274.29	167.95
Re_P	-	0.0054	0.0033	0.0032	0.0034
Fr_x	-	21.27	9.4	11.48	14.91
A_R	m^2	0.0202	0.0289	0.0296	0.0281
X_{50}	m	1.32e-6	1.096e-6	9.85e-7	1.19e-6
C_D	-	424.43	566.86	575.68	557.54
Total pressure drop	Pa	742.68	392.07	460.61	504.98
Solid loading	-	high	high	high	high
Co	kg/kg	8.16e-6	6.93e-5	1.306e-4	2.61e-6
Efficiency	per cent	99.89	99.74	99.78	99.81

3.1.1. The flow pattern: Velocity stream lines

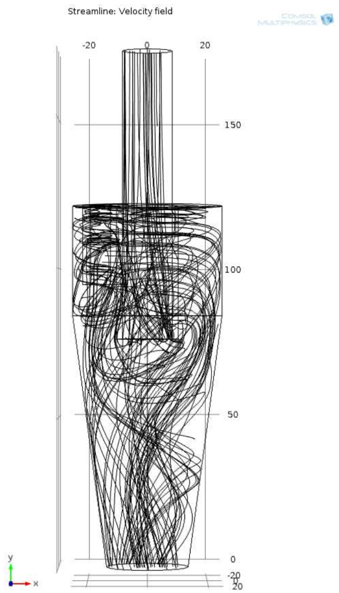
Velocity streamlines fields of the Muschelknautz model-D type (MM-D), Stairmand high efficiency (STR), Lapple general purpose (LAP) and Swift high efficiency (SWF) for one and double slots are plotted in Figure 3.1 and Figure 3.2 respectively. The number of lines in streamlines is the same in both types (100 lines per a cyclone).

In the first part of the simulations, one-input cyclone separator is simulated where lines are asymmetrically distributed in high speed in turbulent solver. On the other hand, in the second part of the simulations, double slot cyclones are smooth vortex with symmetrical shape and low turbulent stream. In other words, streamlines of double input cyclones remain symmetrical with respect to the vertical axis and flow reaches a steady condition, which causes the separation of particles to be better than single slot cyclones.

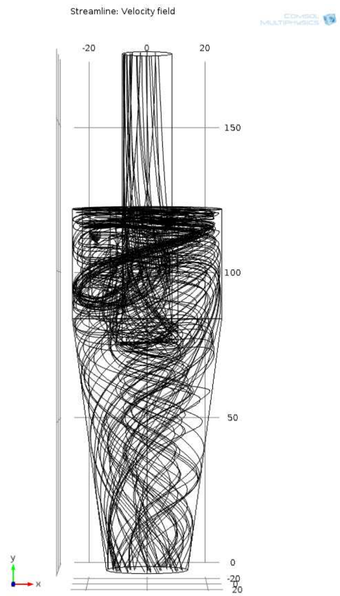
3.1.2. The flow pattern: Velocity field and Pressure profile

Velocity profiles of the Muschelknautz model-D type (MM-D), Stairmand high efficiency (STR), Lapple general purpose (LAP) and Swift high efficiency (SWF) for one and double slots are plotted in Figure 3.3 and Figure 3.4, respectively. Likewise, pressure profiles are plotted in Figures 3.5 and 3.6, for single slot and double slot, respectively. As mentioned before, cyclones that have double input have symmetric velocity distribution and smooth pressure profile.

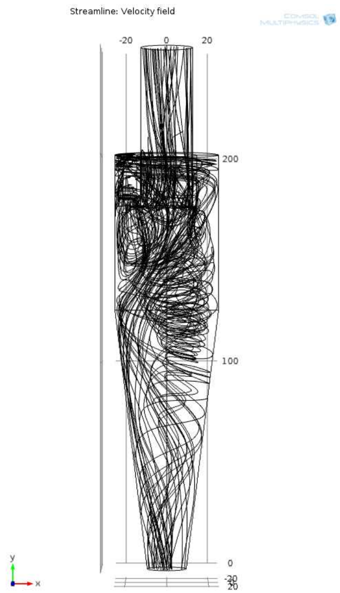
The static pressure reduces radially from the main body walls to the center. A negative pressure region comes out in the central zone as a result of high spinning velocity, especially when a second slot is added on the cyclones. According to the mentioned figures, in a single slot, almost all models have this negative pressure zone, which appears in Muschelknautz model vividly. On the other hand, in double slot cyclones, Muschelknautz and Stairmand models have this region more clearly and more symmetrical. The largest pressure gradient is along the radial direction. Based on the twin vertical motions in the cyclone, the outer spin goes downward and the



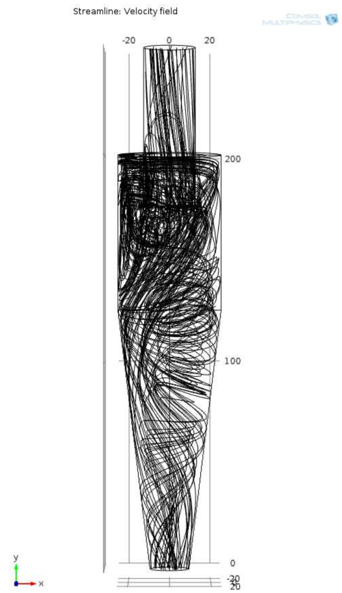
(a) MM-D-L



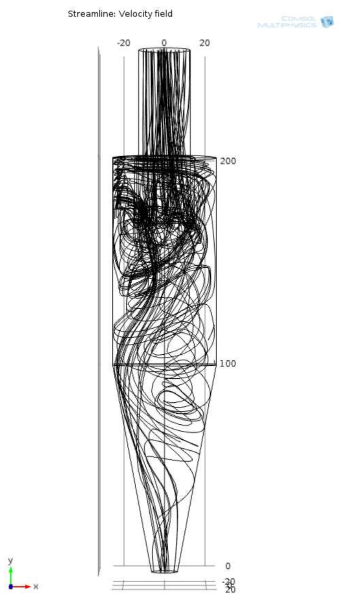
(b) MM-D-T



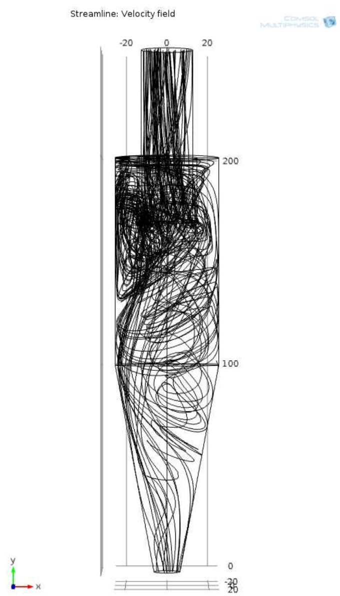
(c) STR-L



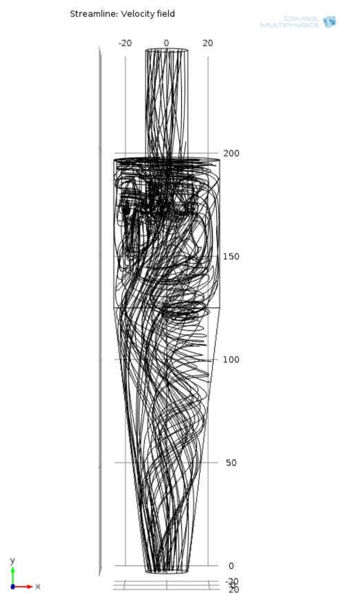
(d) STR-T



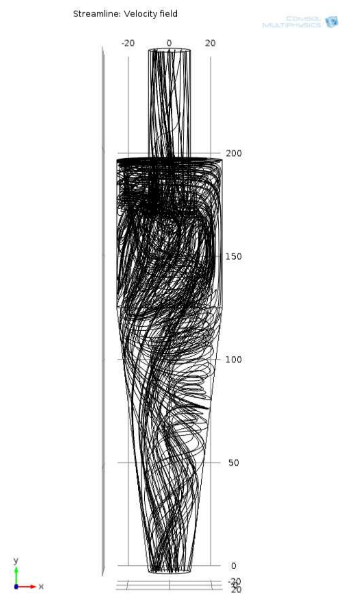
(e) LAP-L



(f) LAP-T

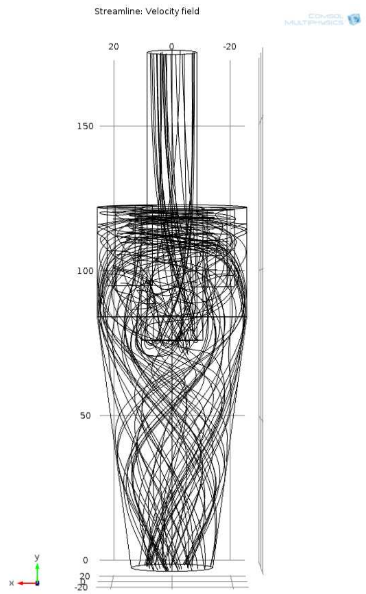


(g) SWF-L

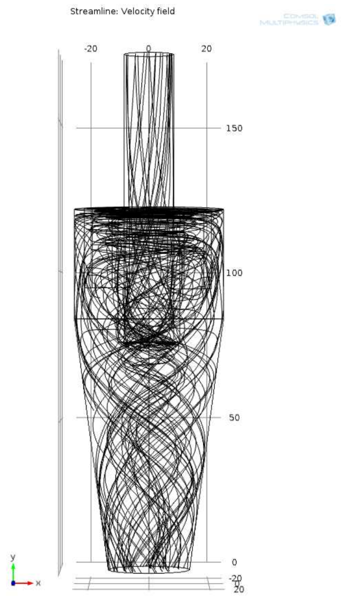


(h) SWF-T

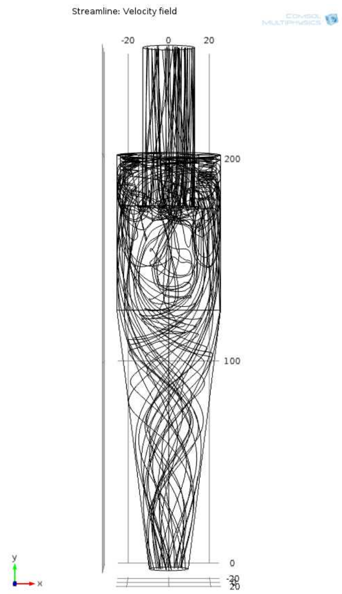
Figure 3.1. Single slot input-Streamlines in laminar(L) & turbulent(T) solvers.



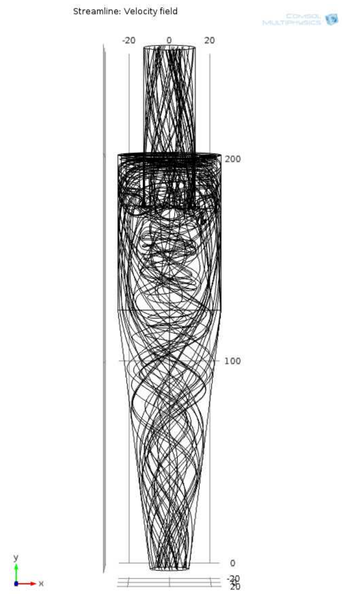
(a) MM-D-L



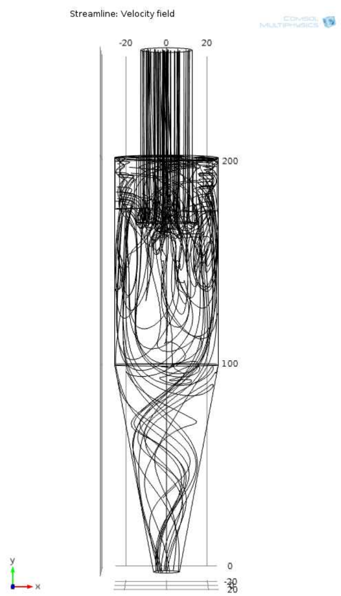
(b) MM-D-T



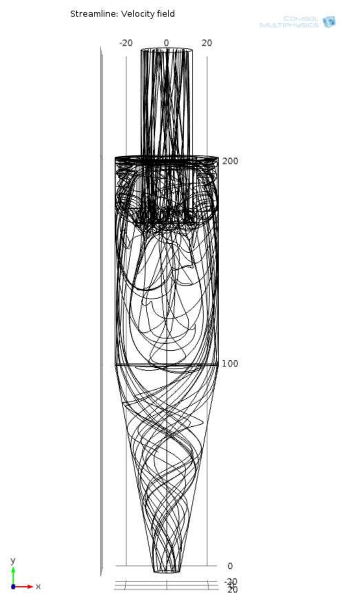
(c) STR-L



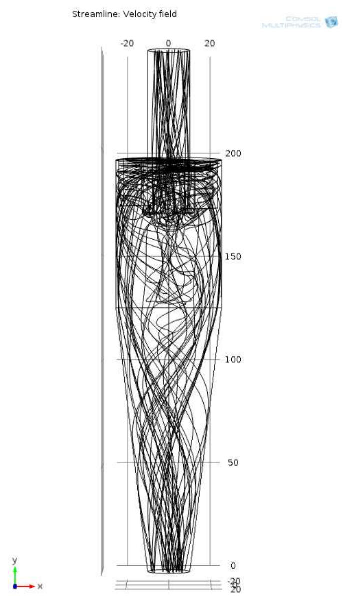
(d) STR-T



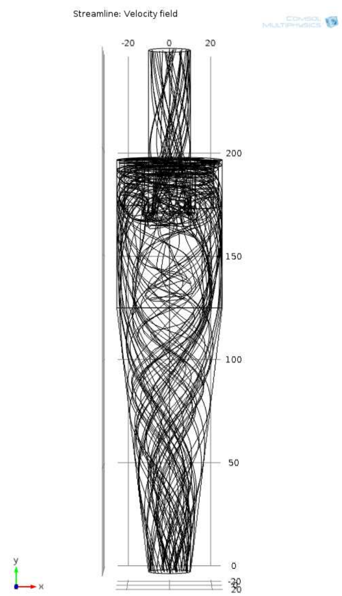
(e) LAP-L



(f) LAP-T

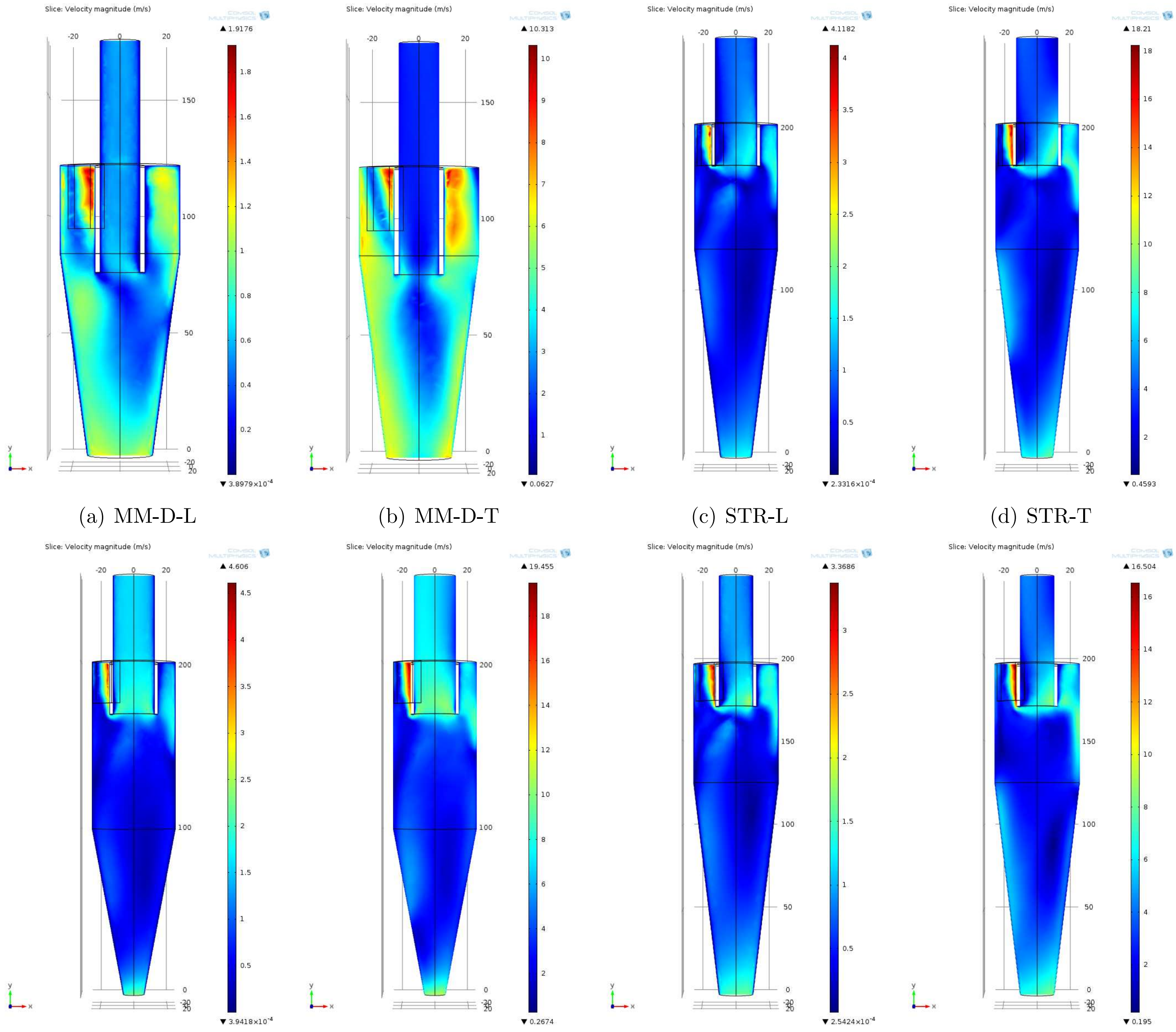


(g) SWF-L



(h) SWF-T

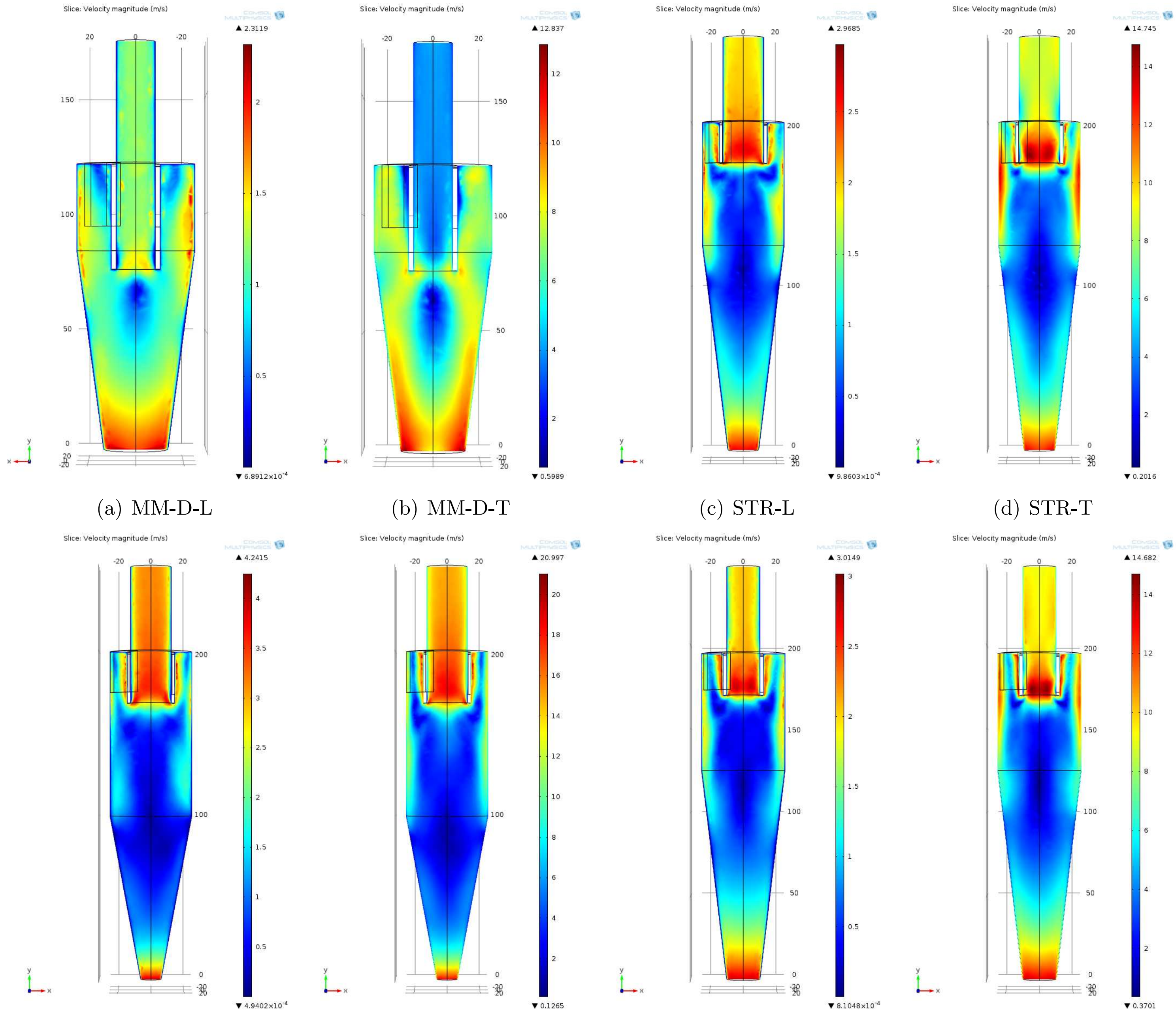
Figure 3.2. Double slot input-Streamlines in laminar(L) & turbulent(T) solvers.



(a) MM-D-L (b) MM-D-T (c) STR-L (d) STR-T

(e) LAP-L (f) LAP-T (g) SWF-L (h) SWF-T

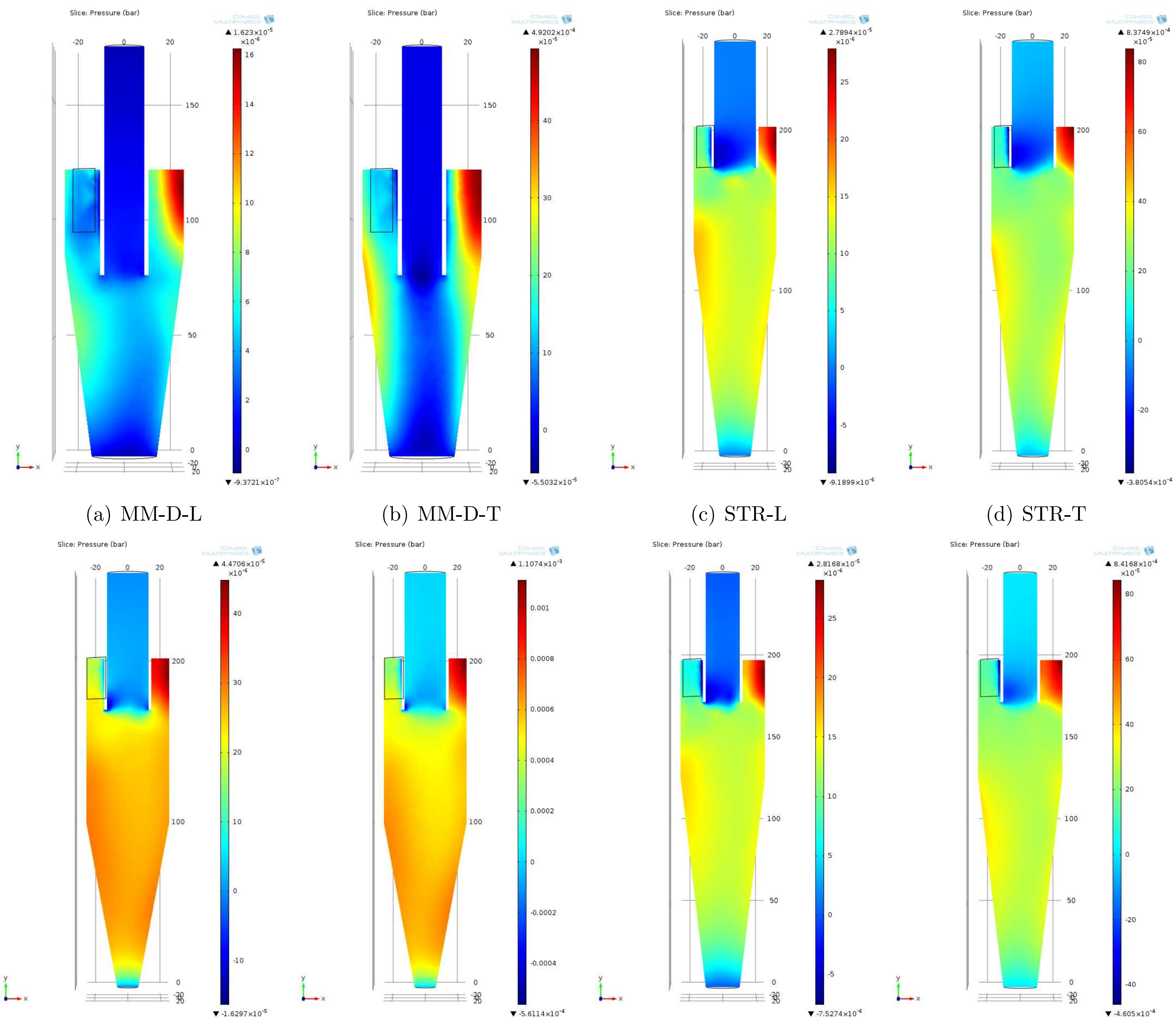
Figure 3.3. Single slot input-Velocity profile in laminar(L) & turbulent(T) solvers.



(a) MM-D-L (b) MM-D-T (c) STR-L (d) STR-T

(e) LAP-L (f) LAP-T (g) SWF-L (h) SWF-T

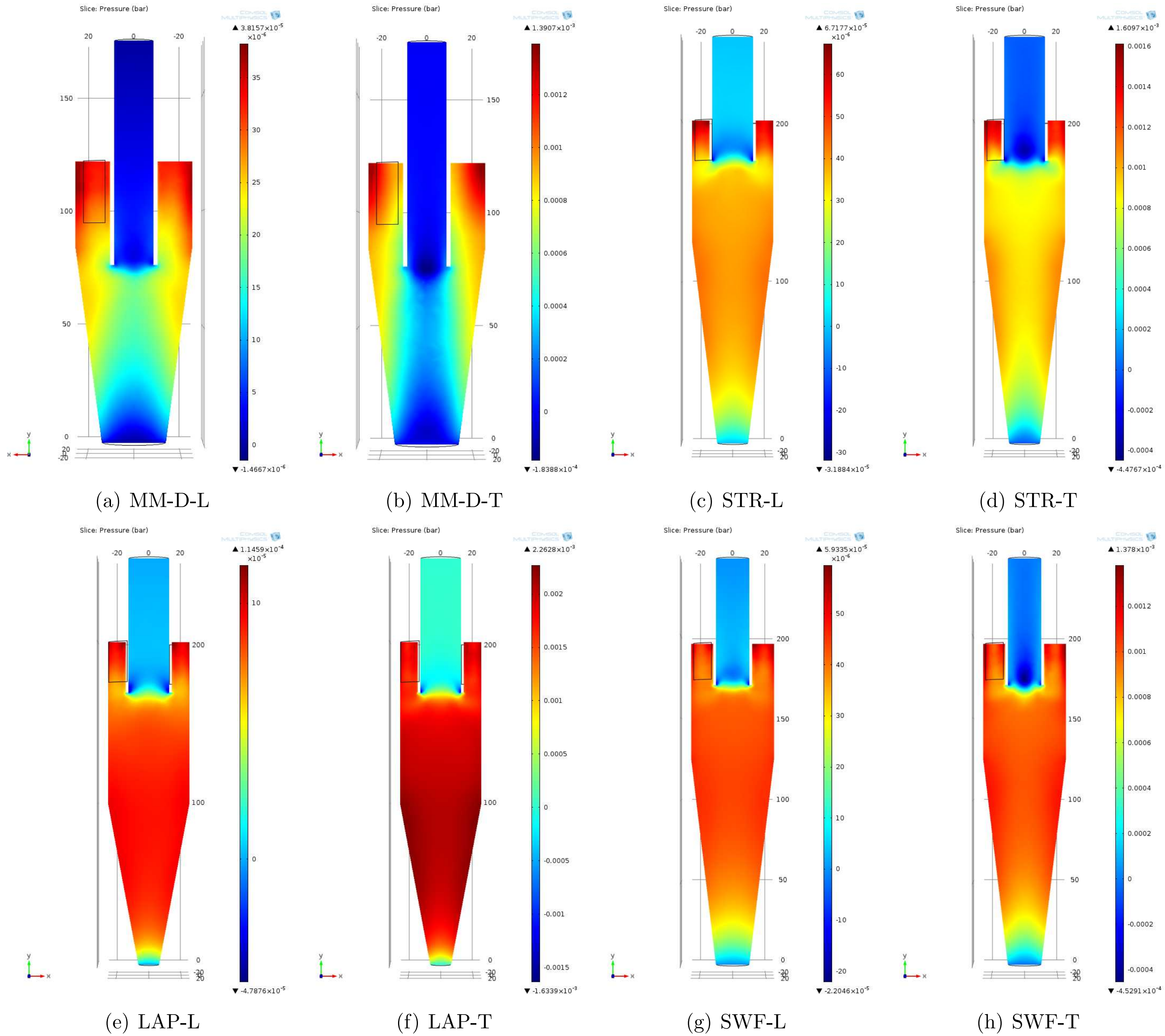
Figure 3.4. Double slot input-Velocity profile in laminar(L) & turbulent(T) solvers.



(a) MM-D-L (b) MM-D-T (c) STR-L (d) STR-T

(e) LAP-L (f) LAP-T (g) SWF-L (h) SWF-T

Figure 3.5. Single slot input-Pressure profile in laminar(L) & turbulent(T) solvers.



(a) MM-D-L (b) MM-D-T (c) STR-L (d) STR-T

(e) LAP-L (f) LAP-T (g) SWF-L (h) SWF-T

Figure 3.6. Double slot input-Pressure profile in laminar(L) & turbulent(T) solvers.

inner vortex moves upward. The largest amount of the static pressure is in the Lapple model especially in double slot cyclone. The tangential velocity magnitudes of cyclones are very similar, except for Muschelknautz model in which the velocity of inside of the cyclone is a little higher than the others, exclusively in double slot cyclone. Hence, in the pressure drop patterns, MM-D is the lowest pressure drop in comparison to the other models. Consequently, a good collection efficiency can be obtained when the pressure drop inside the cyclone decreases.

3.1.3. Particle trajectory

The geometrical parameters in cyclone separators affect the flow field and performance parameters significantly. In the previous figures and tables some of the physical approaches of cyclonic separation are shown for the sake of the initial judgment of cyclone's performance. However, by using particle tracing for fluid flow module in the COMSOL, we can find out the exact performance of each cyclone. To visualize the calculated factors, the line chart is drawn afterwards. The particle trajectory of the models is highlighted in Figures 3.7 and 3.8 for single slot and double slot cyclones using 2 m/s input velocity, respectively. The number of input particles are the same in all four models and it is 100, where the diameters of these particles vary from 2 μm to 8 μm. ($d = 2, 4, 6, 8\mu m$).

In these figures, it is easy to distinguish the cyclone which has a higher performance in removing particles. The amount of particles that each cyclone could separate from dirty gas is separately shown. Figures 3.7 and 3.8 depict the particle trajectory of single slot and double slot cyclones when the input velocity is 2 m/s. The blue line in the graph shows the number of input particles and the other lines with different colors beneath the blue one are related to other models. When the four models are compared, it is seen that Muschelknautz D type has the most efficient cyclone among others in laminar flow with 2 m/s input velocity. Indeed, this cyclone could separate 2 μm particles with approximately 90 percent efficiency in single and double slots. Increasing the input velocity of cyclone from 2 m/s up to 10 m/s and simultaneously switching from laminar to turbulent solver would change the results. This change can be under-

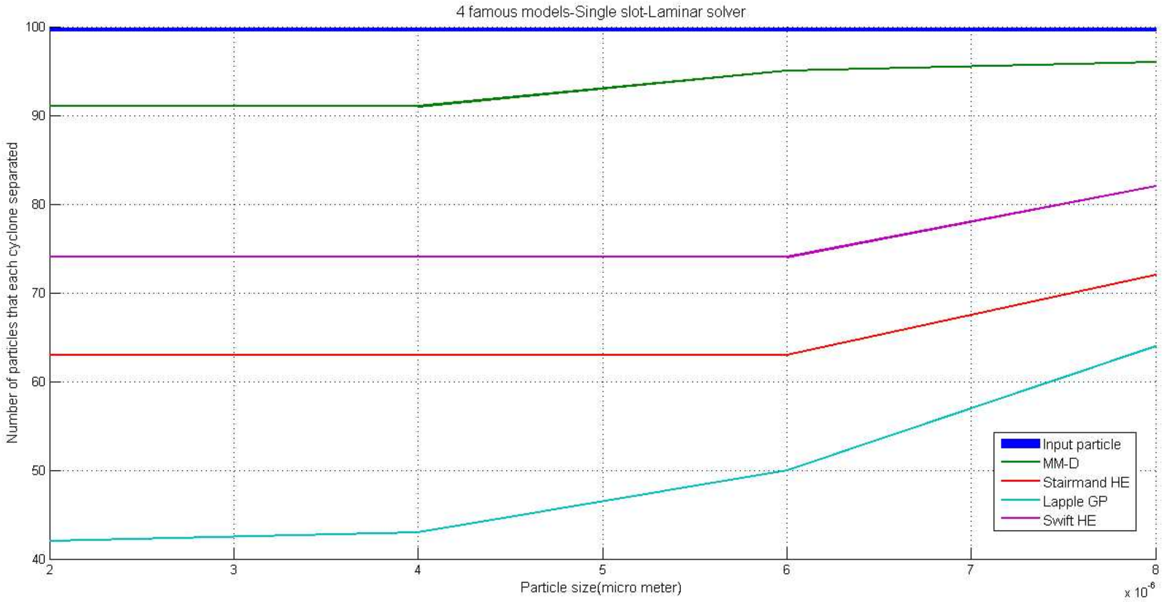


Figure 3.7. Famous models-Single slot-with low input velocity.

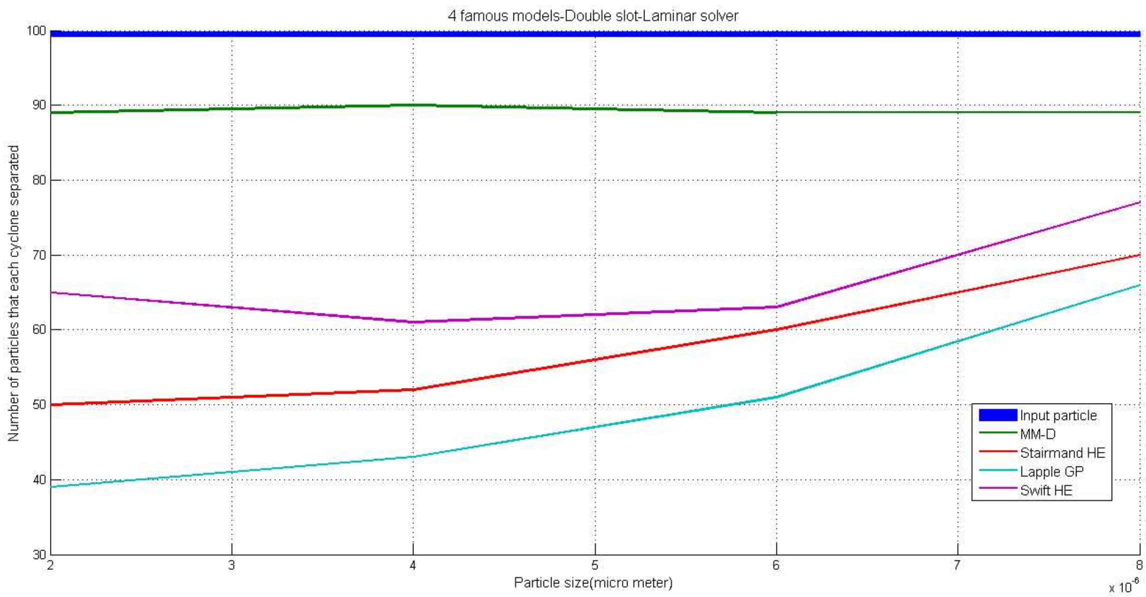


Figure 3.8. Famous models-Double slot-with low input velocity.

stood from the slop of the graphs vividly. Figures 3.9 and 3.10 illustrate the number of particles that each cyclone has separated when the input velocity is increased to 10 m/s.

Flow rate or input velocity to evaluate the overall collection efficiency in the cyclones is a part of the formulations that mentioned in previous chapter. For this reason, separation efficiency will rise with the inlet velocity. In other words, collection efficiency and entrance velocity have a direct relation. Although the separation efficiency of the double slot is often higher than the single slot, this phenomenon is directly related to the geometric parameters most of the time. In the first case study, exclusively Muschelknautz model-D type has the highest overall efficiency among the other models, not only in the single inlet but also with double slot. This effect enhances the overall efficiency of cyclones with a contribution of the number of inlet and increasing the entrance velocity by $0 - 12.5\%$ and $0.25 - 4.27\%$ in the modeled cyclones. In low velocity, the overall efficiency decreases to 12.5 % but when the input velocity increases to 10 m/s, the overall efficiency of cyclones improves about more than four percent, especially when double slot is used. In other words, in low input velocity when the second slot is added, the collection efficiency decreases in all models, especially in Swift model. The collection efficiency of double slot cyclones will rise except Swift and Stairmand models, when input velocity is 10 m/s.

Four cyclones with different geometries have been simulated, using Muschelknautz method and COMSOL multi-physics, to study the effects of input velocity and the number of inputs on the four prominent models on the cyclone separator performance and flow pattern. Outcomes of the study show that Muschelknautz-D type has the best performance compared to the other types. The others are Swift high efficiency, Stairmand high efficiency and Lapple general purpose. In the case of these models, the data in the Tables 3.2 and 3.3 should be used for predictions. They illustrate that increasing the average Reynolds number of cyclones is the same as the increasing of overall performance of cyclones, according to the both approaches. By increasing the input velocity, the performance of cyclone will boost, especially when the double slot input is used.

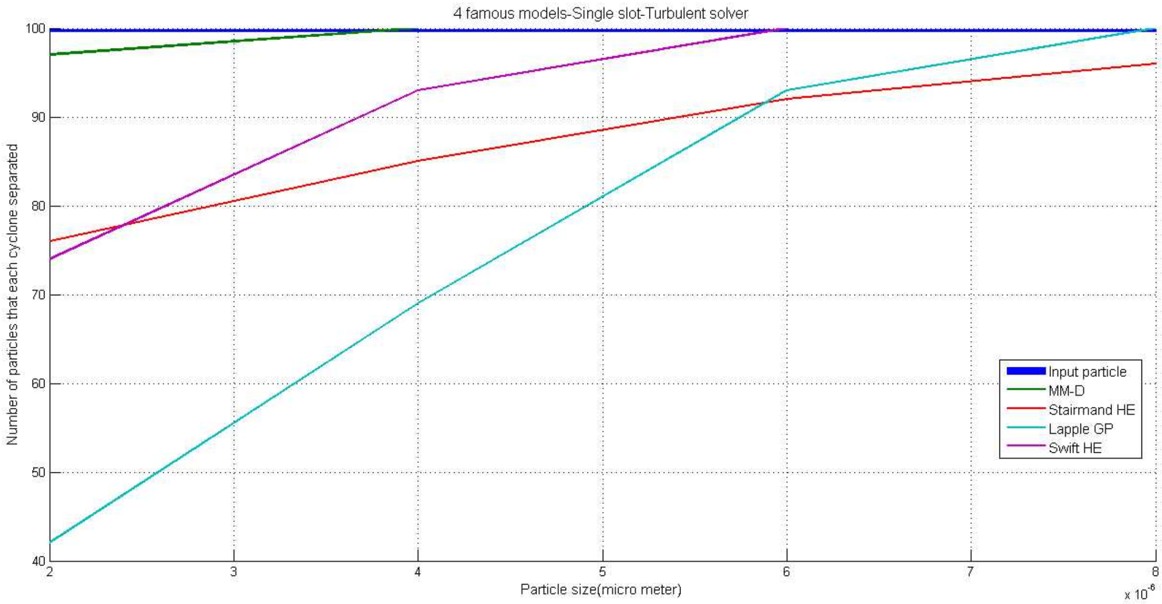


Figure 3.9. Famous models-Single slot-with high input velocity.

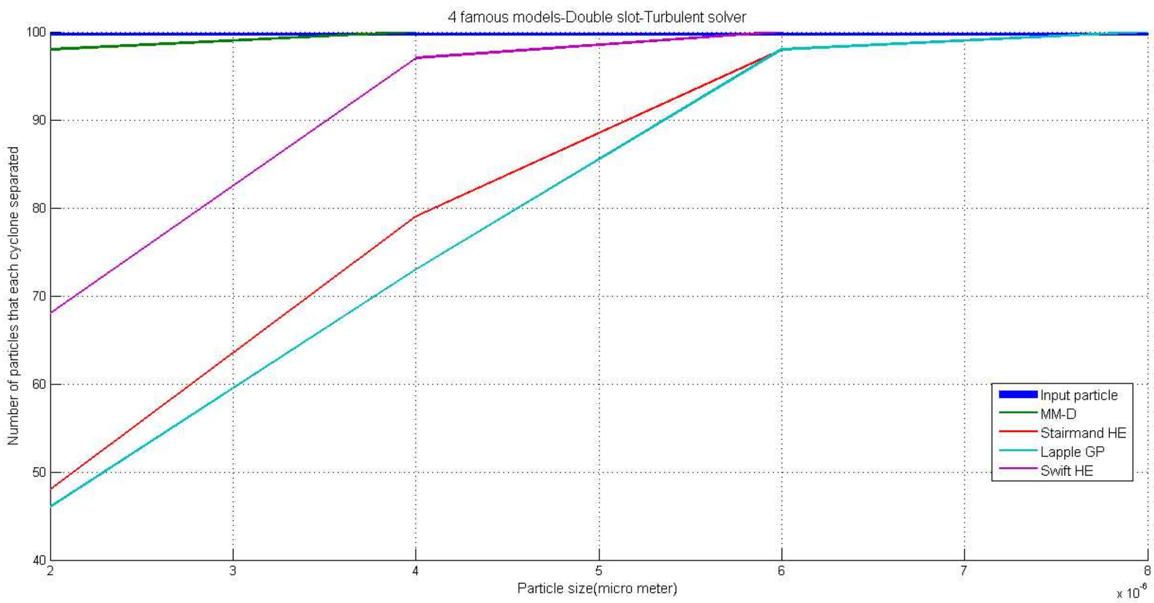


Figure 3.10. Famous models-Double slot-with high input velocity.

3.2. SECOND CASE STUDY: SS MODEL

In this section, we define prototype models based on an original model, and then the performance of the new models are measured and compared to the original one. The efficiency of these produced models increases by modification of the slot size and vortex finder length. Also, a second slot is added to the model to check the separation efficiency. SS model's coefficients are in fact the ratio of cyclone body diameters and all of combinations of **a** and **b** are calculated. The original input sizes are $\mathbf{a} = 0.5\mathbf{D}$ and $\mathbf{b} = 0.2\mathbf{D}$ (or $\mathbf{a} = 25mm$ and $\mathbf{b} = 10mm$ when **D**=50mm). The aim of this research is to understand the effects of different slot size and to assess the response of this modification and also to understand how the performance of cyclone in collecting the particles with a high efficiency changes. Adding another slot will give the opportunity to compare the previous results with single slot cyclone. Table 3.6 shows the constructed models using a full combination of new independent variables obtained by adding and subtracting one to and from initial independent variables. According to the following table, the length of vortex finder is not constant and it varies as a function of **a** which leads to a decrease in short circuits between input gas and the vortex finder without any separation. In fact, model SS5 has no modifications in it. (a, b and S are in meter.)

Table 3.6. The values of the independent variables.

Model name	Inlet height(a)	Inlet width(b)	Vortex finder length(S)
SS1	0.02	0.005	0.032
SS2	0.02	0.01	0.032
SS3	0.02	0.015	0.032
SS4	0.025	0.005	0.04
SS5	0.025	0.01	0.04
SS6	0.025	0.015	0.04
SS7	0.03	0.005	0.048
SS8	0.03	0.01	0.048
SS9	0.03	0.015	0.048

The results of the variables obtained using COMSOL for single slot and double slot cyclone are tabulated in Tables 3.7 and 3.8, respectively. The data in the tables, show properties of cyclones such as average magnitude of velocity (m/s) and average Reynolds number of the clean gas on top of the vortex finder pipe. According to the tables, minimum average velocity belongs to SS1 and the maximum one belongs to SS9. Same results can be observed for average Reynolds numbers. Some fluctuation can be seen in 5th and 6th steps of nine steps in both slot models, in comparison to the base model (SS5).

Table 3.7. SS MODEL-Single slot input-COMSOL's results.

Model	V-Laminar	V-Turbulent	Re-Laminar	Re-Turbulent
SS1	0.31481	1.72157	7.70841	37.8019
SS2	0.53271	2.66647	12.94466	59.64859
SS3	0.71577	3.3348	17.589	76.06676
SS4	0.40058	2.23255	9.70484	48.5599
SS5	0.68587	3.47205	16.85333	78.79199
SS6	0.92567	4.39061	22.25983	98.60982
SS7	0.48499	2.74875	11.91758	61.19467
SS8	0.83403	4.28284	20.30356	96.31788
SS9	1.13379	5.50741	27.44469	125.1231

Input surface area of the SS1 is the smallest and SS9 is the largest one among all models. By adding the second slot to the models, all values in the tables are approximately multiplied by two; however, the sequence of cyclones do not change same as the one in a single slot form, especially in low input velocity.

Table 3.8. SS MODEL-Double slot inputs-COMSOL's results.

Model	V-Laminar	V-Turbulent	Re-Laminar	Re-Turbulent
SS1	0.67681	3.79374	15.23356	84.60524
SS2	1.22304	6.45479	28.72249	139.60661
SS3	1.6416	8.18582	38.86512	184.04721
SS4	0.86064	4.80236	20.0109	102.66442
SS5	1.52424	8.12938	37.19983	187.71439
SS6	2.04473	10.362	49.90544	241.0278
SS7	1.05893	5.84852	24.63557	126.20857
SS8	1.84237	9.75329	43.72231	221.05784
SS9	2.45145	12.47157	58.16786	282.44835

Mathematical analysis with the Muschelknautz method (MM) has been used to figure out the influence of geometrical diversity on collection efficiency. All in all, it is apparent from the previous discussions that the effect of the inlet dimensions on the flow field, velocity and Reynolds number on the particle separation are significant. The results of Muschelknautz method are indicated in Tables 3.9 and 3.10 for two main input velocities (2 and 10 m/s) and Figure 2.2 illustrates the placement of velocities inside the cyclone. These results are the same as the previous case study that was just for one slot.

Although, there are some differences between the calculation method of COMSOL and Muschelknautz, somehow the results are considerably close. The first table depicts cyclones with the inlet velocity 2 m/s. The efficiency row shows the separation efficiency of each model with the same condition of inlet velocity and inlet particle sizes. The minimum efficiency belongs to SS9 with 70.82 percent of separation, and the maximum one belongs to SS4 with 89.39 percent. SS5 with 84 percent efficiency places in fourth rank. While the inlet velocity increases to 10 m/s (Table 3.10), the efficiencies of cyclones are changing. For instance, SS3 has the maximum efficiency in comparison to the other cyclones. SS5 is in seventh place and SS1 is the same as the previous one in the lowest separation. Comparing the tables, it can be seen that SS9 almost always has the lowest efficiency while it has the maximum normal volumetric flow rate, Reynolds number and any kind of velocity (i.e. $V_{\Theta\omega}$, $V_{Z\omega}$, $V_{\Theta CS}$) and also Fr_x and pressure drop. On the other hand, SS1 has the lowest amount of velocities, Reynolds number and pressure drop in both low and high inlet velocity. Using the second slot for cyclones, the amount of volumetric flow rate of each cyclone is doubled and based on the results of Table 3.8, velocities and Reynolds numbers are raised more than twice.

Eventually, the two approaches (CFD and mathematical analysis) are partly matching. There are minor differences in magnitude of some values. The data set is focused on CFD results because in Muschelknautz method, the turbulent flow is not considered. Nevertheless, the result of the geometrical modifications on both velocity and cut-off diameter are presented in tables.

From the results, we can conclude that in low inlet velocity, the SS4 has the maximum collection particle efficiency. By increasing the inlet velocity to 10 m/s, SS3 has the best efficiency in collection of the particles compared to the other models. As these devices are usually used in high speed conditions, the results of high inlet velocity are reliable to be used in an actual condition. Consequently, changing the dimension of slots plays a crucial role in boosting the performance of cyclones and changing the pressure drop of cyclones.

The general trend based on the tables is the cut-size diameter and collection efficiency decreases while cyclone inlet height and pressure drop increase, due to the weakness of the vortex. The other perspective is that by increasing cyclone inlet width, the cut-size diameter decreases and boosts the cyclone pressure drop. According to the information about the cyclone separator, the performance of cyclonic separation can be enhanced by increasing solid loading size for attending high solid loading sizes. For that reason the pressure drop reduces significantly when the inlet velocity is high where there is a turbulent flow pattern.

3.2.1. The Flow Pattern: Velocity Stream Lines

Velocity streamline fields of the SS models are plotted in Figures 3.11, 3.12 and 3.13 for one slot and in Figures 3.14, 3.15 and 3.16 for double slots. The number of lines in streamlines are the same in both types which is equal to 100 lines per cyclone.

In the first step of the simulations, cyclone separator with one input is simulated where lines are distributed asymmetrically, at high speeds in turbulent solvers. In the second simulation, double slot cyclones are smooth vortex with symmetrical shape and low turbulent stream. In other words, in double input cyclones, streamlines remain symmetric with respect to the vertical axis while flow reaches a steady condition. This causes the separation of particles and acts better than single slot cyclones. Another important aspect in simulation is the inlet's shape differences. It causes a change of the velocity streamlines non-symmetric distribution. Three models just have the smooth vortex inside the cyclone, in both single and double slot. They are SS1, SS4 and SS7. It is observed that the most disturbance of stream lines occurs when the inlet width increases; as a result, a better collection efficiency can be predicted when the inlet width increases.

Table 3.9. Single slot- SS MODEL- Vin=2 m/s -MM's results.

	Units	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8	SS9
Normal vol. flowrate	Nm^3/h	1.29	2.42	3.42	1.63	3.11	4.43	1.96	3.78	5.45
$V_{\Theta\omega}$	m/s	2.288	2.57	2.43	2.287	2.58	2.43	2.26	2.57	2.43
$V_{Z\omega}$	m/s	0.174	0.327	0.462	0.22	0.42	0.599	0.265	0.51	0.736
$V_{\Theta CS}$	m/s	0.349	0.82	1.188	0.485	1.123	1.579	0.619	1.4	1.92
Re_R	-	22.49	37.05	44.83	28.26	47.15	57.03	33.79	56.71	68.76
Re_P	-	0.0018	0.002	0.0022	0.0019	0.0021	0.0025	0.0019	0.0023	0.0028
Fr_x	-	0.782	1.468	2.074	0.988	1.886	2.68	1.18	2.29	3.3
A_R	m^2	0.0313	0.0313	0.0313	0.0319	0.0319	0.0319	0.0326	0.0326	0.0326
X_{50}	m	9.027e-6	5.18e-6	4.123e-6	7.27e-6	4.308e-6	3.568e-6	6.219e-6	3.82e-6	3.27e-6
C_D	-	812.5	777.28	724.38	803.74	746.94	676.44	790.51	713.40	628.63
Total pressure drop	Pa	4.095	8.164	10.44	4.96	10.41	13.82	5.76	12.64	17.62
Solid loading	-	high	high	high	high	high	high	high	high	high
Co	kg/kg	3.26e-6	1.143e-5	1.632e-5	4.081e-6	1.796e-5	3.02e-5	6.53e-6	4.48e-5	1.06e-4
Efficiency	per cent	88.68	84.34	86.50	89.39	84	83.88	86.39	75.12	70.82

Table 3.10. Single slot- SS MODEL- Vin=10 m/s -MM's results.

	Units	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8	SS9
Normal vol. flowrate	Nm^3/h	6.42	12.1	17.1	8.15	15.5	22.15	9.81	18.9	27.25
$V_{\Theta\omega}$	m/s	11.39	12.87	12.19	11.43	12.88	12.16	11.38	12.88	12.17
$V_{Z\omega}$	m/s	0.868	1.63	2.31	1.10	2.09	2.99	1.32	2.55	3.68
$V_{\Theta CS}$	m/s	4.12	8.42	10.79	5.46	10.40	12.61	6.62	11.81	13.89
Re_R	-	114.35	189.97	231.31	144.67	241.4	294.6	173.50	291.55	355.1
Re_P	-	0.0018	0.0023	0.0029	0.002	0.0027	0.0037	0.0021	0.0032	0.0046
Fr_x	-	3.89	7.34	10.37	4.94	9.4	13.43	5.95	11.46	16.53
A_R	m^2	0.0313	0.0313	0.0313	0.0319	0.0319	0.0319	0.0326	0.0326	0.0326
X_{50}	m	1.78e-6	1.19e-6	1.07e-6	1.52e-6	1.10e-6	1.06e-6	1.38e-6	1.08e-6	1.07e-6
C_D	-	823.21	715.14	618.80	782.69	644.42	534.5	740.34	578.92	468
Total pressure drop	Pa	155.19	304.31	380.02	188.14	376.18	477.03	217.10	443.30	573.83
Solid loading	-	high	high	high	high	high	high	high	high	high
Co	kg/kg	3.26e-6	1.143e-5	1.632e-5	4.081e-6	1.796e-5	3.02e-5	6.53e-6	4.48e-5	1.06e-4
Efficiency	per cent	99.77	99.89	99.99	99.85	99.89	99.87	99.85	99.80	99.68

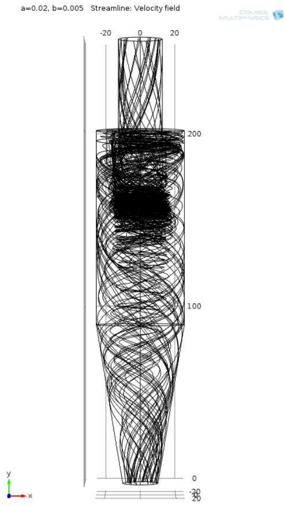
Reviewing these figures, two observations can be made: when the flow is asymmetric, stream lines start from cylindrical part of cyclone but expand near the cone bottom and there is a large variation in the long inlet length and wide inlet width in this region. According to mentioned figures, the extent of asymmetry is not only a function of the cyclone geometry and boundary condition at the cone bottom, but also the operating condition like the gas flow rate. Consequently, the vortex shape and the number of turns will be stable as the cyclone inlet width decreases.

3.2.2. The Flow Pattern: Velocity Field and Pressure Profile

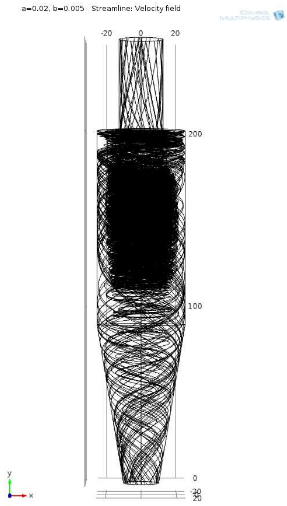
The tangential velocity is one of the crucial factors inside the cyclones. The flow fluid establishes a strong centrifugal force to separate particles from the gas stream. Moreover, the tangential velocity gradient in X-Y direction will be studied for all the nine SS models. A mid-section view of velocity magnitude are plotted in Figures 3.23, 3.24 and 3.25 for single slot and Figures 3.26, 3.27 and 3.28 for double slot cyclones. Also a mid-section view of each cyclone is depicted for static pressure profiles as shown in Figures 3.17, 3.18 and 3.19 for single slot and Figures 3.20, 3.21 and 3.22 for double slot cyclones.

The correlation of both inlet height and width dimension in the cyclone separator has the same influence on the pressure drop. On the other hand, the cut-size diameter is vulnerable to a change in the inlet width in comparison with the variation of inlet height.

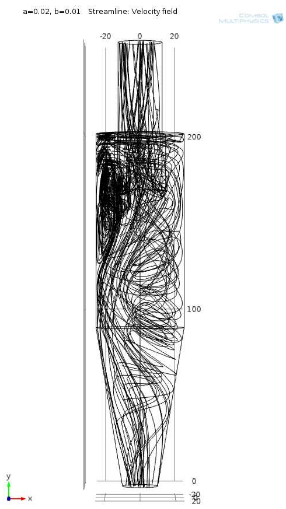
Here, it is shown that both height of cyclone and inlet's dimension cause the same phenomenon. According to the Figures 3.11, 3.12, 3.13 and 3.14, 3.15, 3.16, this problem can be seen in some models but the problem in single slot is much worse than double slot due to symmetrical vortexes in the double inlets. In the double inlet cyclones, it is not a critical issue. However, there are some strokes just on SS8 and SS9. Hence, their efficiency is lower than the other models. As far as the figures show, the tangential velocity and static pressure of these models differ.



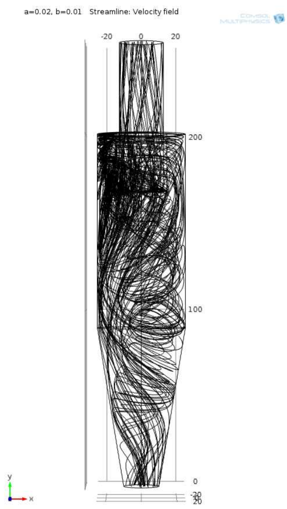
(a) SS1-L



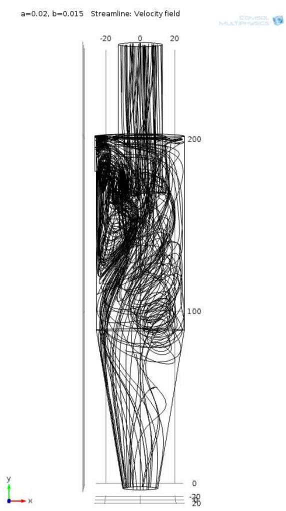
(b) SS1-T



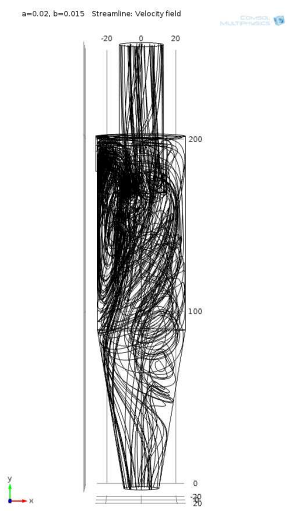
(c) SS2-L



(d) SS2-T

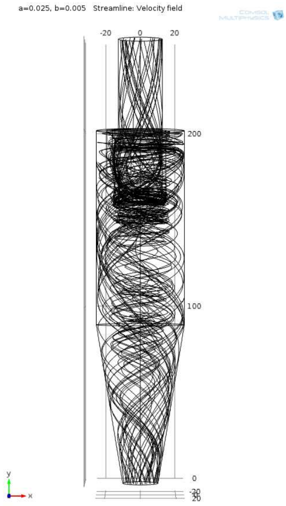


(e) SS3-L

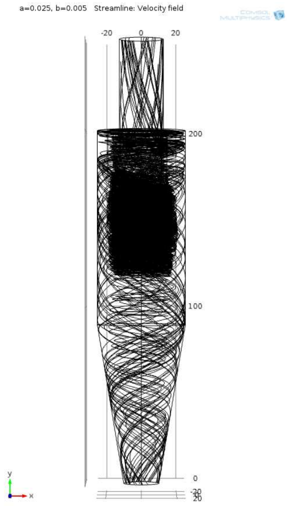


(f) SS3-T

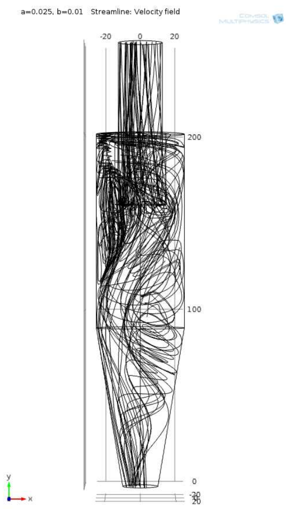
Figure 3.11. Single slot input-SS MODELS-Streamlines in laminar(L) & turbulent(T) solvers (a-f).



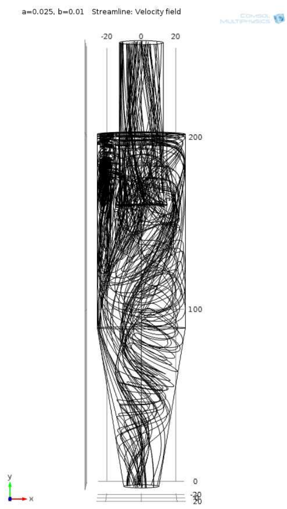
(g) SS4-L



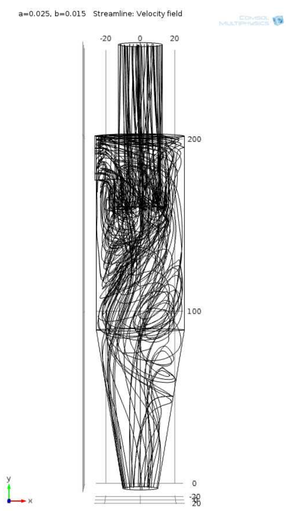
(h) SS4-T



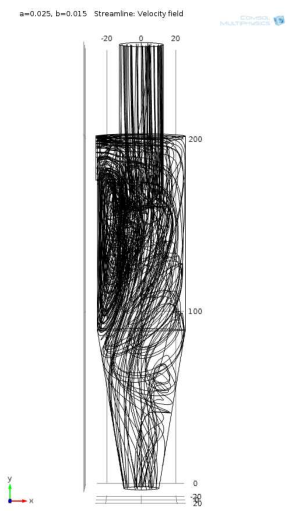
(i) SS5-L



(j) SS5-T

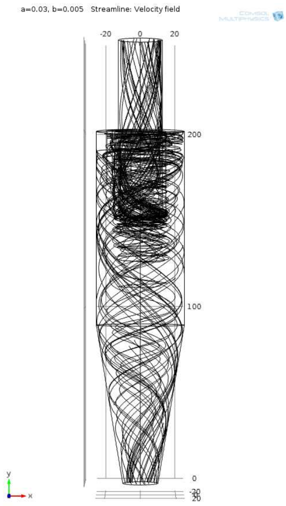


(k) SS6-L

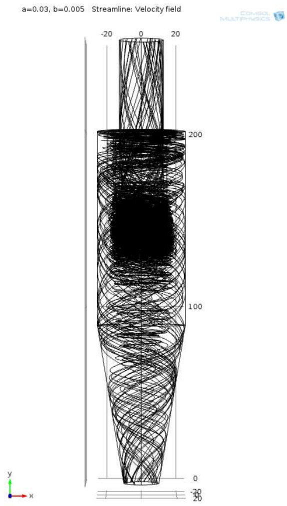


(l) SS6-T

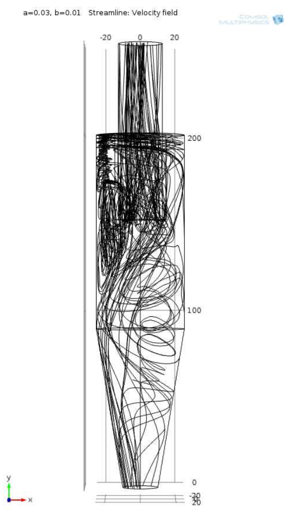
Figure 3.12. Single slot input-SS MODELS-Streamlines in laminar(L) & turbulent(T) solvers (g-l).



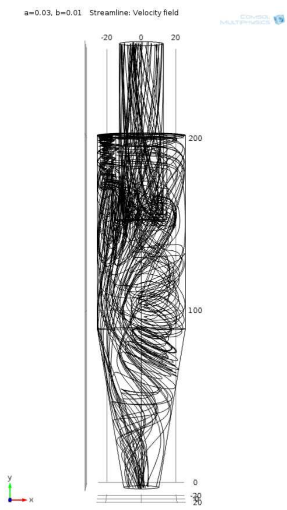
(m) SS7-L



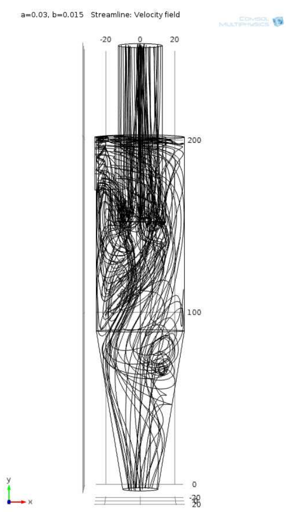
(n) SS7-T



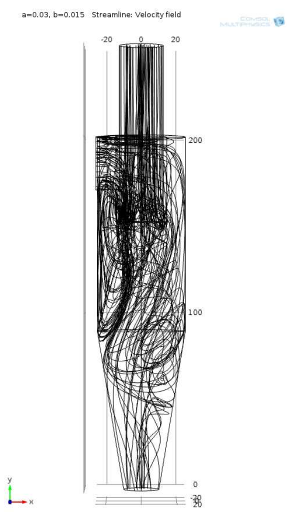
(o) SS8-L



(p) SS8-T

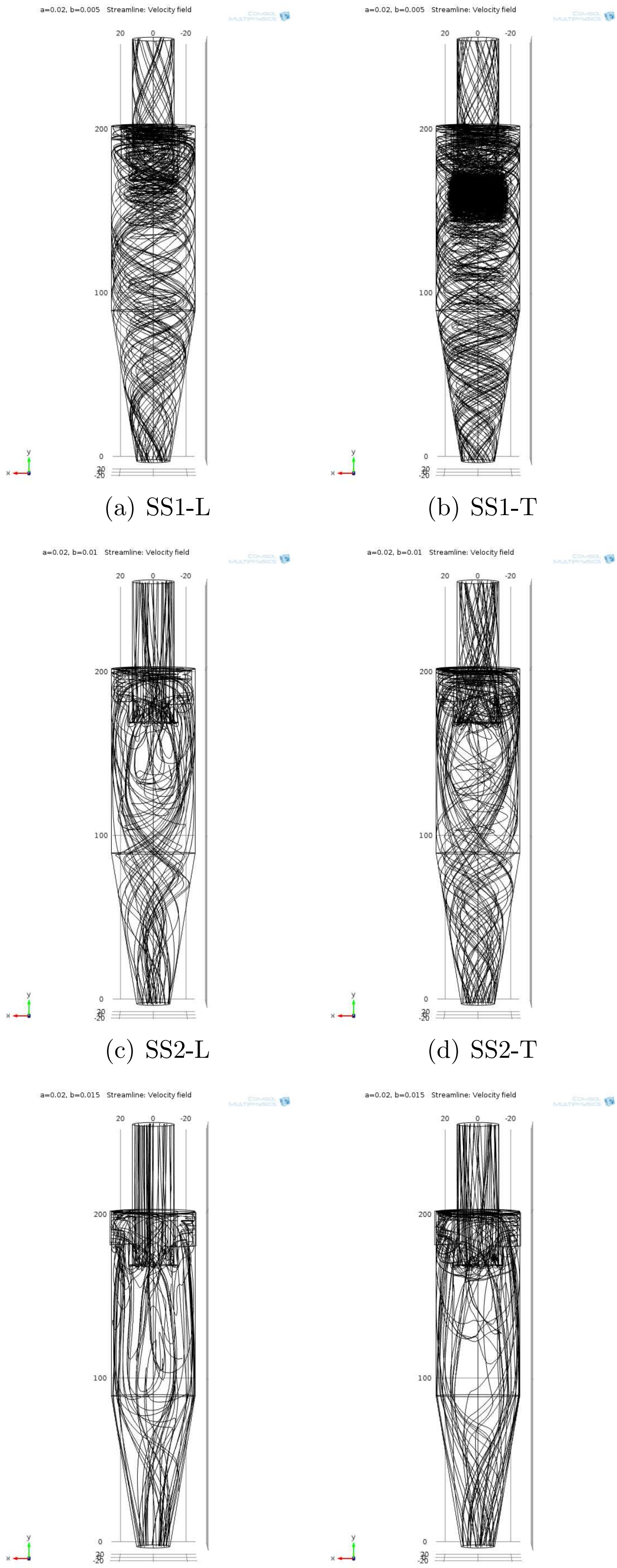


(q) SS9-L



(r) SS9-T

Figure 3.13. Single slot input-SS MODELS-Streamlines in laminar(L) & turbulent(T) solvers (m-r).

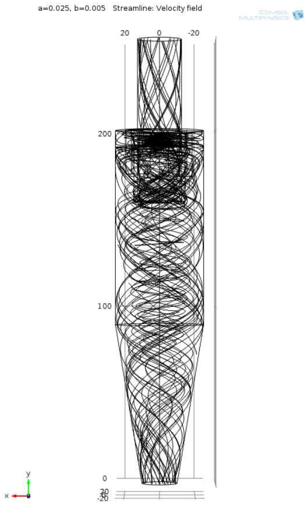


(a) SS1-L (b) SS1-T

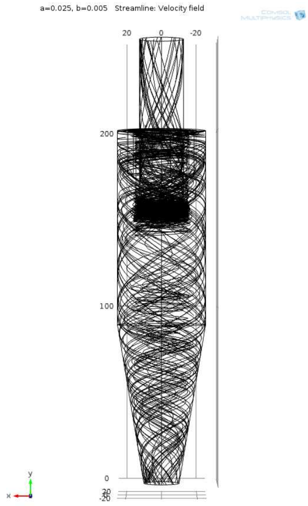
(c) SS2-L (d) SS2-T

(e) SS3-L (f) SS3-T

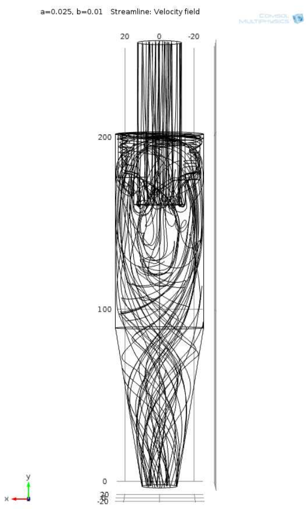
Figure 3.14. Double slot inputs-SS MODELS-Streamlines in laminar(L) & turbulent(T) solvers (a-f).



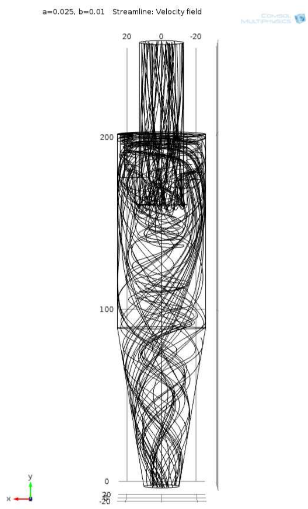
(g) SS4-L



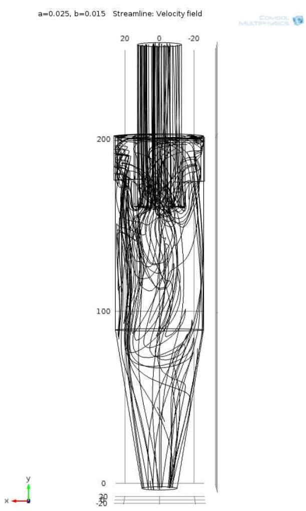
(h) SS4-T



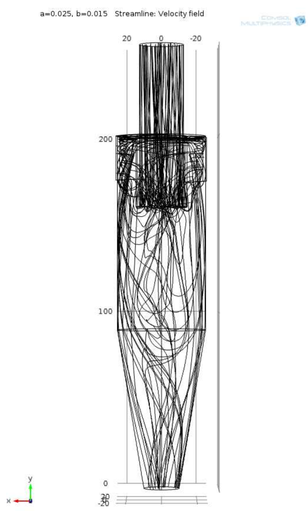
(i) SS5-L



(j) SS5-T

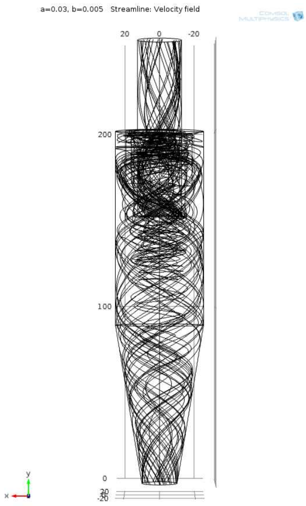


(k) SS6-L

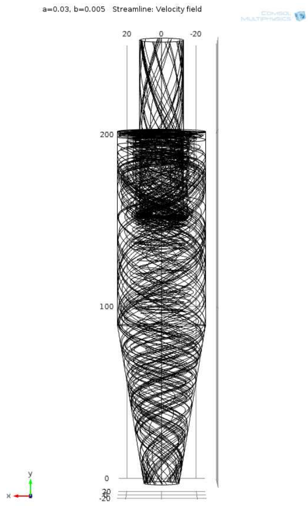


(l) SS6-T

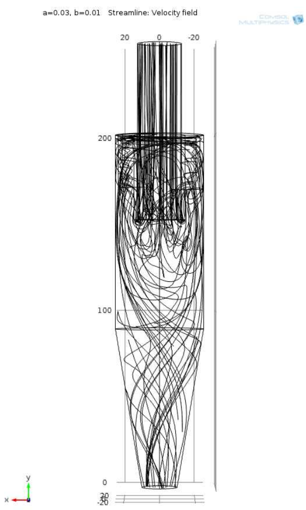
Figure 3.15. Double slot inputs-SS MODELS-Streamlines in laminar(L) & turbulent(T) solvers (g-l).



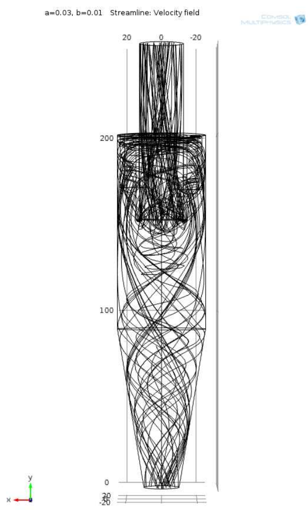
(m) SS7-L



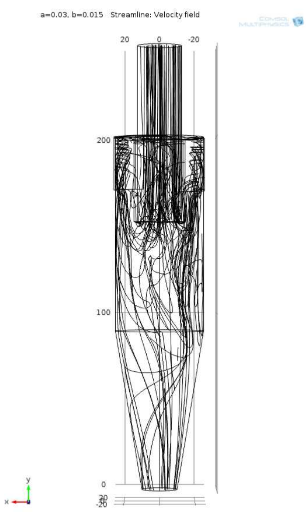
(n) SS7-T



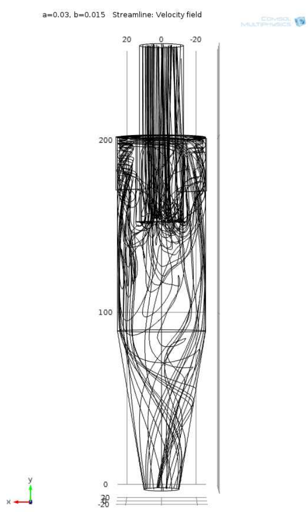
(o) SS8-L



(p) SS8-T



(q) SS9-L

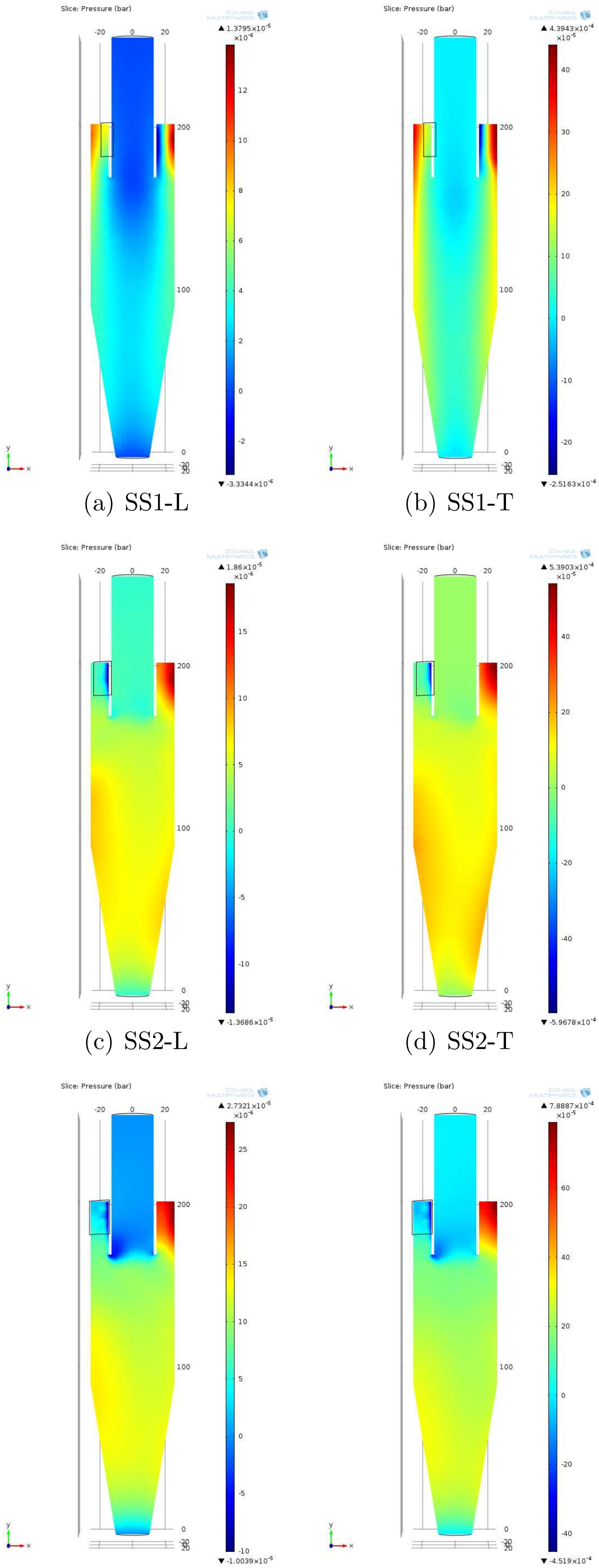


(r) SS9-T

Figure 3.16. Double slot inputs-SS MODELS-Streamlines in laminar(L) & turbulent(T) solvers (m-r).

Rationally, the static pressure reduces from the main body walls to the mid vertical axis radially. A negative pressure region appears in the central zone of the cyclone as a result of turbulent vortex, especially when the double slot input is used. According to the figures, in both models (single and double slot), almost all models have this negative pressure zone, especially in SS1, SS2, SS4, SS7 models which appear vividly. On the other hand, some models have a huge pressure loss in the mid-zone of cyclone. This occurs in SS3, SS6 and SS9, especially when they have two slots and high entrance velocity. There is a relation between inlet height and width and pressure loss. This phenomenon can occur in both single and double slot cyclones, when inlet width increases. The static pressure also has a direct relation with inlet height of cyclone. Comparing single and double slot cyclones, it can be seen that when the inlet width increases, the static pressure varies in average from 245.07 % to 327.76 % in low velocity input, respectively. And in high speed entrance, average pressure fluctuation is from 611.1 % to 249.8 % in one slot and two slot cyclones, respectively. As a result, a good collection efficiency can occur when the pressure drop inside the cyclone decreases because declining the static pressure can decrease when the inlet width increases especially when double slot cyclone and high input velocity are used. Another way to control the pressure drop variation is changing the inlet height. Increasing the length of the inlet causes a rise of static pressure from 118.89 % to 144.43% in single slot cyclone when inlet velocity increases from 2 to 10 m/s in average; but, this happens for double slot cyclones, from 133.15 % to 128.57 % in average, the same condition that is mentioned before.

The tangential velocity is one of the important circumstances for cyclone design. The velocity pattern is not similar for the modeled cyclones. In the single slot cyclones, as the inlet width size increases, the tangential velocity of the mid-zone of the cyclone increases. Meanwhile, the velocity rises due to the growth of the inlet height. This phenomenon occurs in both low and high input velocity. In other words, when the inlet height increases, the tangential velocity of the middle region decreases about 61.31 % and 35.5 % with low and high input velocity in single slot cyclone, respectively (in average). As the inlet width increases, the velocity of the mentioned region decreases to 357.85 % and 196.58 % in laminar and turbulent condition in single slot, respectively.

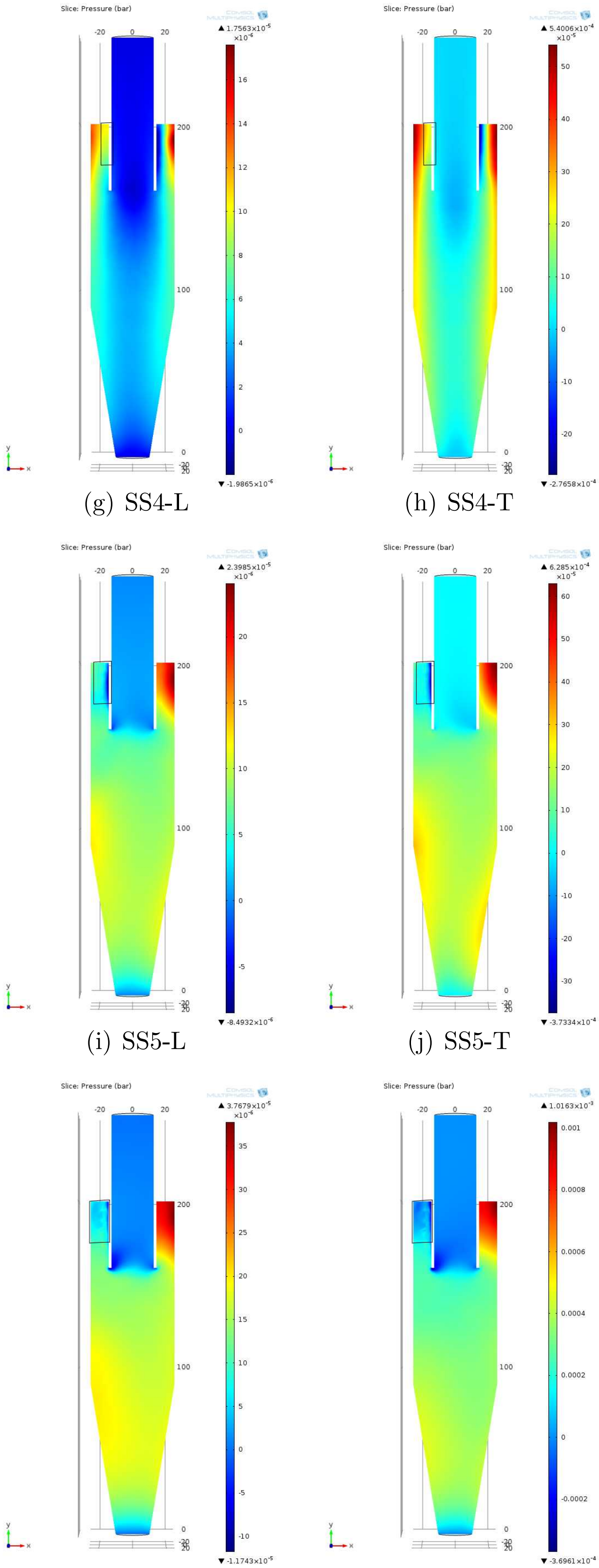


(a) SS1-L (b) SS1-T

(c) SS2-L (d) SS2-T

(e) SS3-L (f) SS3-T

Figure 3.17. Single slot input-SS MODELS-Pressure profile in laminar(L) & turbulent(T) solvers (a-f).

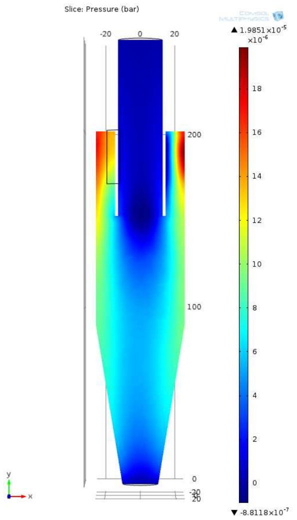


(g) SS4-L (h) SS4-T

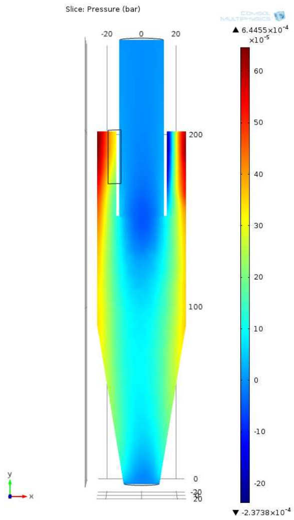
(i) SS5-L (j) SS5-T

(k) SS6-L (l) SS6-T

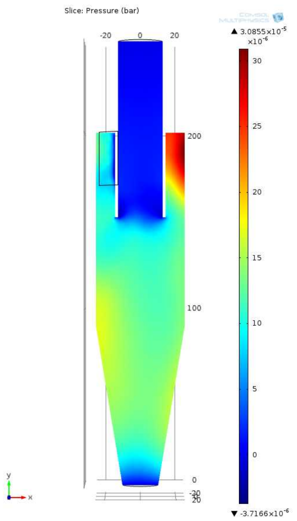
Figure 3.18. Single slot input-SS MODELS-Pressure profile in laminar(L) & turbulent(T) solvers (g-l).



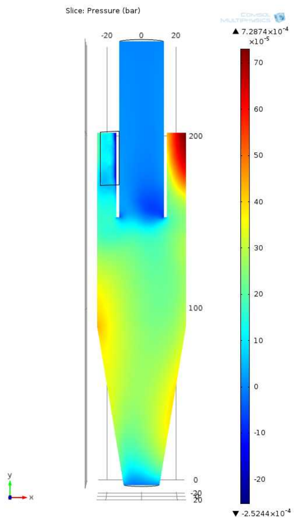
(m) SS7-L



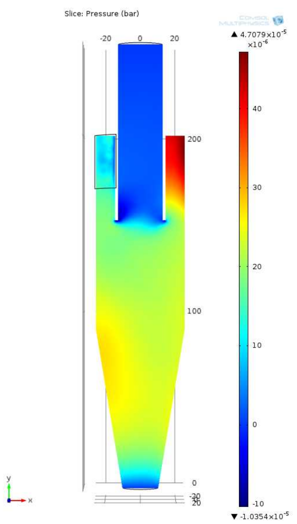
(n) SS7-T



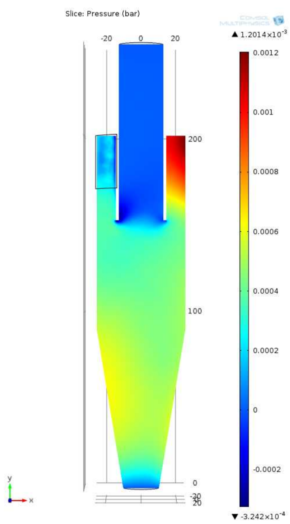
(o) SS8-L



(p) SS8-T

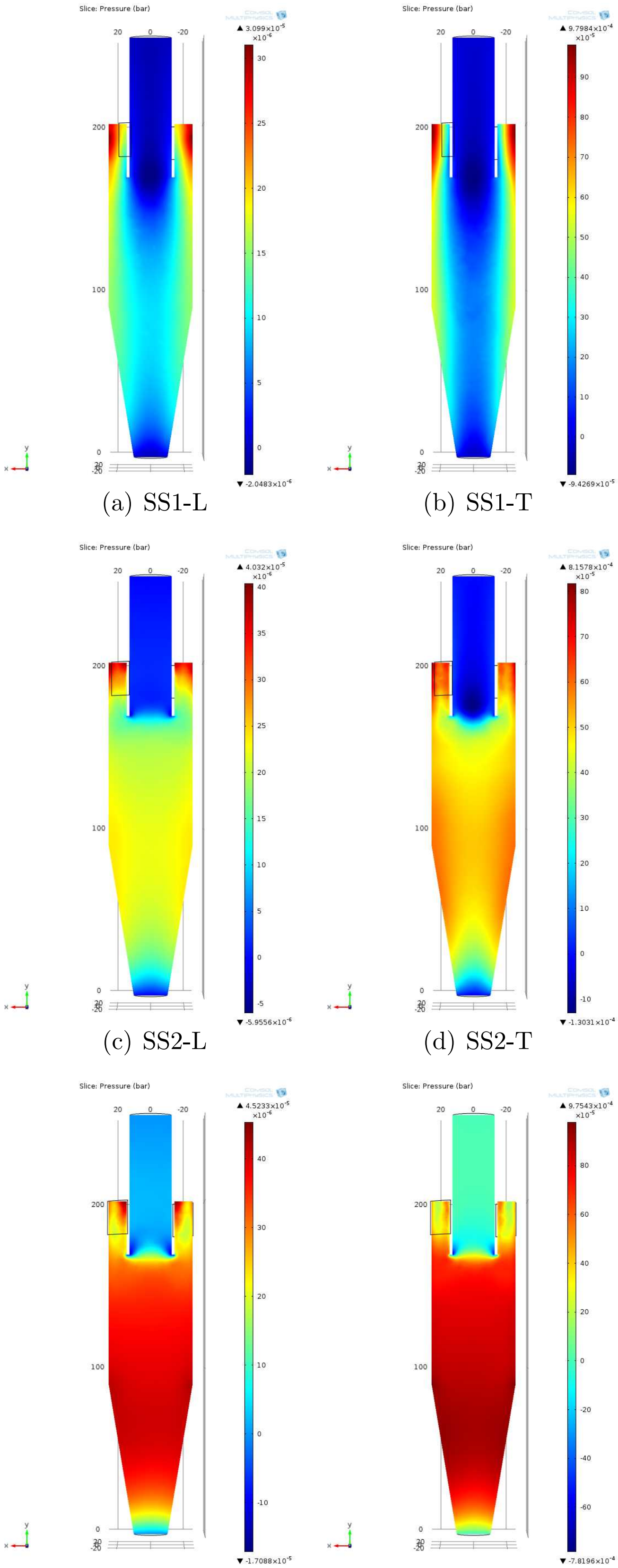


(q) SS9-L



(r) SS9-T

Figure 3.19. Single slot input-SS MODELS-Pressure profile in laminar(L) & turbulent(T) solvers (m-r).

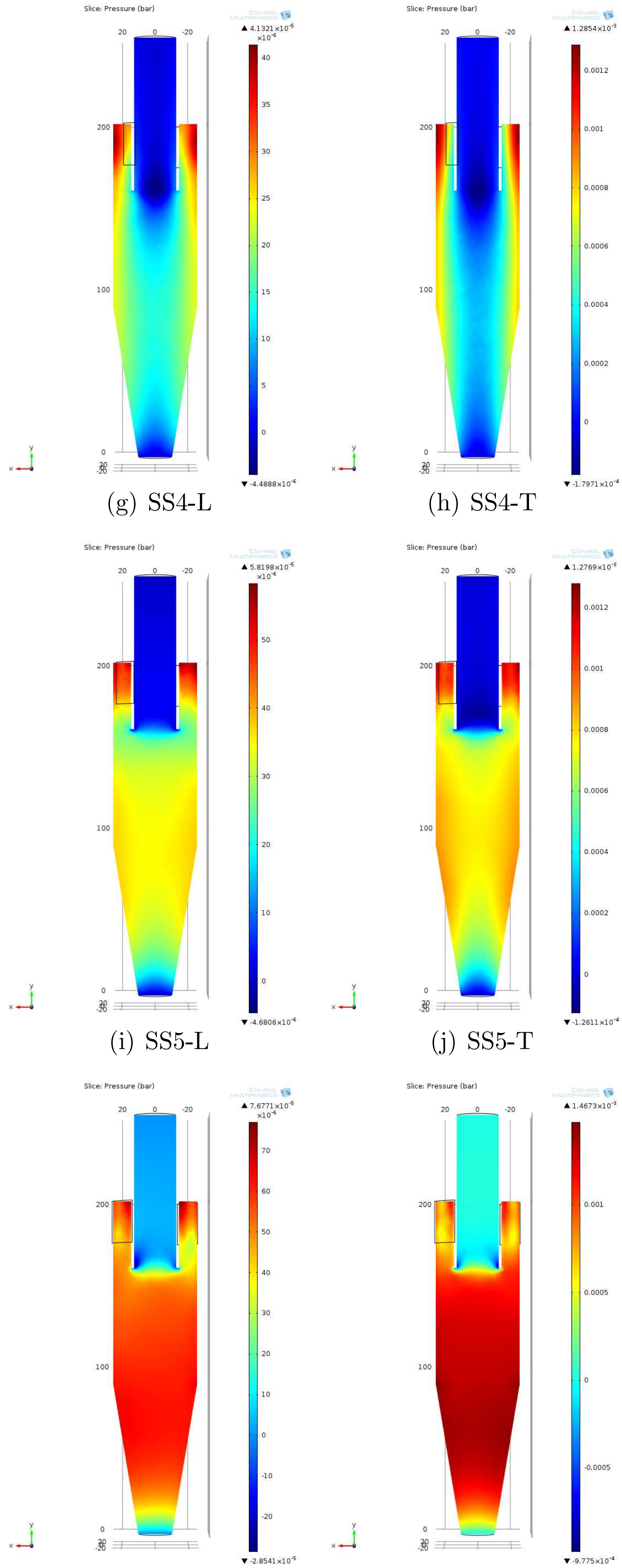


(a) SS1-L (b) SS1-T

(c) SS2-L (d) SS2-T

(e) SS3-L (f) SS3-T

Figure 3.20. Double slot inputs-SS MODELS-Pressure profile in laminar(L) & turbulent(T) solvers (a-f).

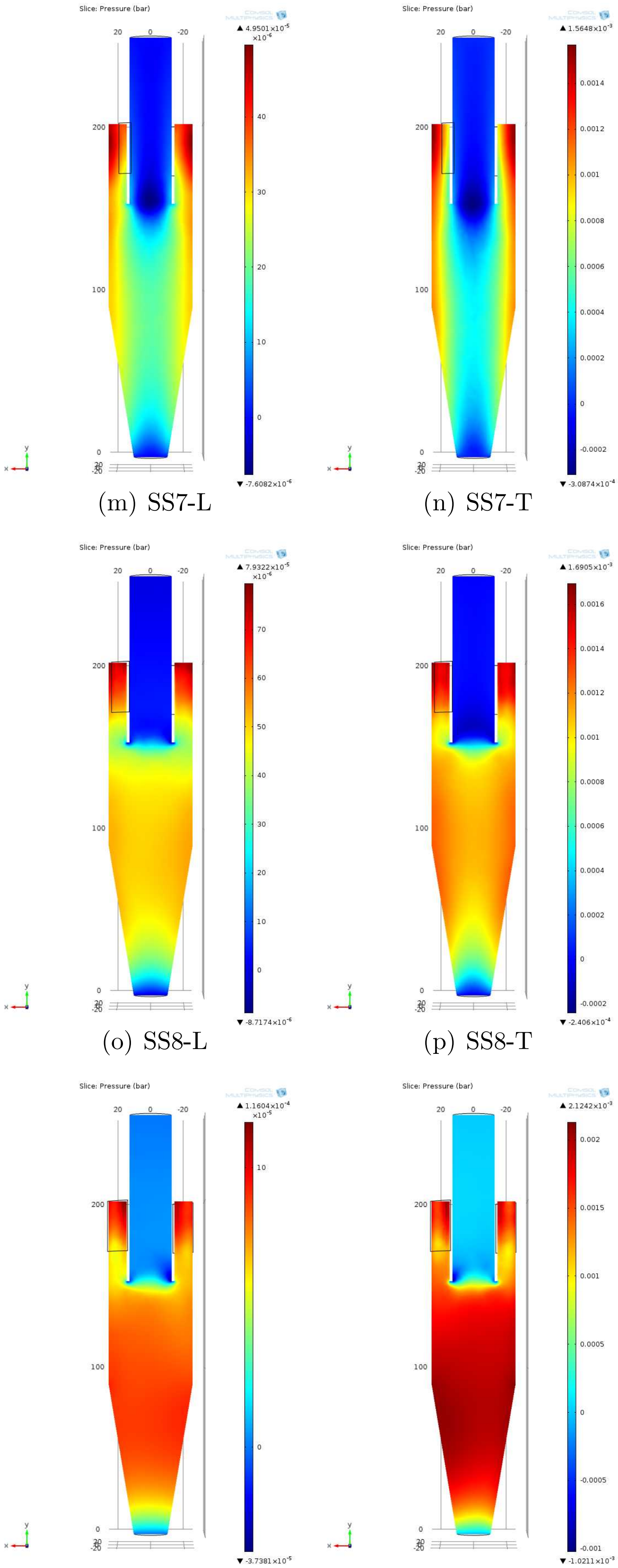


(g) SS4-L (h) SS4-T

(i) SS5-L (j) SS5-T

(k) SS6-L (l) SS6-T

Figure 3.21. Double slot inputs-SS MODELS-Pressure profile in laminar(L) & turbulent(T) solvers (g-l).



(m) SS7-L (n) SS7-T

(o) SS8-L (p) SS8-T

(q) SS9-L (r) SS9-T

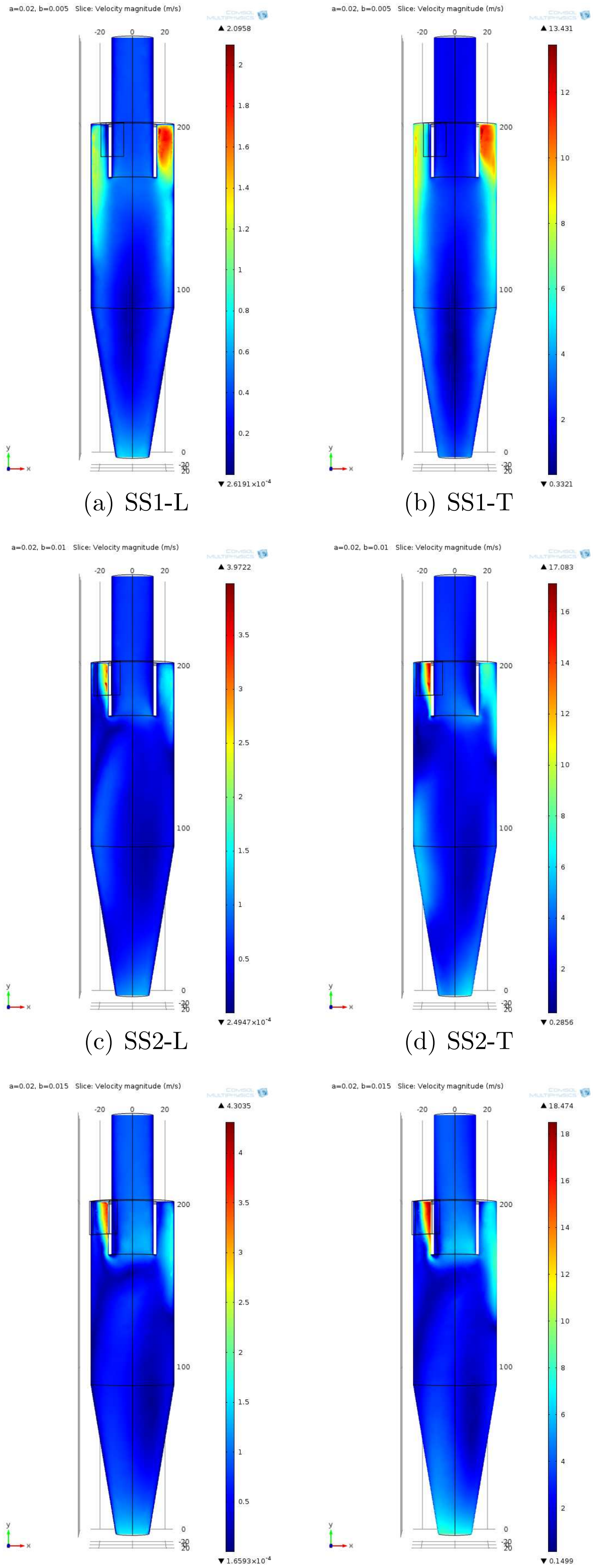
Figure 3.22. Double slot inputs-SS MODELS-Pressure profile in laminar(L) & turbulent(T) solvers (m-r).

Surprisingly, the story of the tangential velocity has changed in the double slot cyclones. In these types of cyclones, because of some symmetrical velocity patterns, the velocity of the middle zone fluctuates, especially SS2, SS5 and SS8 models, when the size of inlet width increases. On the other hand, as the inlet height increases, the velocity rises. These changes are measured in the center of cyclone. While inlet height increases from 0.02 to 0.03 m, the tangential velocity declines from 271.56 % to 21.12 %, when input velocity changes from low to high speed. While inlet width rises from 0.005 to 0.015 m, velocity magnitude changes from 147.71 % until 17.95 % when the input velocity increases from low to high. For that reason, when the tangential velocity increases, the collection efficiency of cyclone increases as well. There is another phenomenon that sometimes the designers of cyclone separator encounter. The inlet width is never wider than the gap between vortex finder and the inner main body. As a consequence, some of the gas flow will hit the vortex finder, thus this part of flow will not establish a vortex inside the cyclone and for that reason, this phenomenon causes some vibration, noise and decreases the total collection efficiency of cyclone.

From the figures, the variation of cyclones in pressure drop and velocity magnitude, which depends on the number of inlets can be seen. The cyclone has one inlet; consequently, the flow should be asymmetric but in two slots in the most models, there is a symmetric profile. There is a fully developed flow (outflow boundary condition) in the vortex finder exit section. Actually, there is no guarantee that the flow is fully developed. The flow would still be developed through the vortex finder after exiting the cyclone.

3.2.3. Particle Trajectory

The geometrical parameters in cyclone separators significantly affect the flow field and performance parameters. In the previous figures and tables, changing the inlet height and width and length of the vortex finder is depicted. Effects of cyclonic separation is shown for purposes of initial judgment of cyclone's performance. However, using particle tracing module for fluid flow part in the COMSOL, the exact performance of particle separation in each cyclone can be found out. For visualization, the calculated



(a) SS1-L (b) SS1-T

(c) SS2-L (d) SS2-T

(e) SS3-L (f) SS3-T

Figure 3.23. Single slot input-SS MODELS-Velocity profile in laminar(L) & turbulent(T) solvers (a-f).

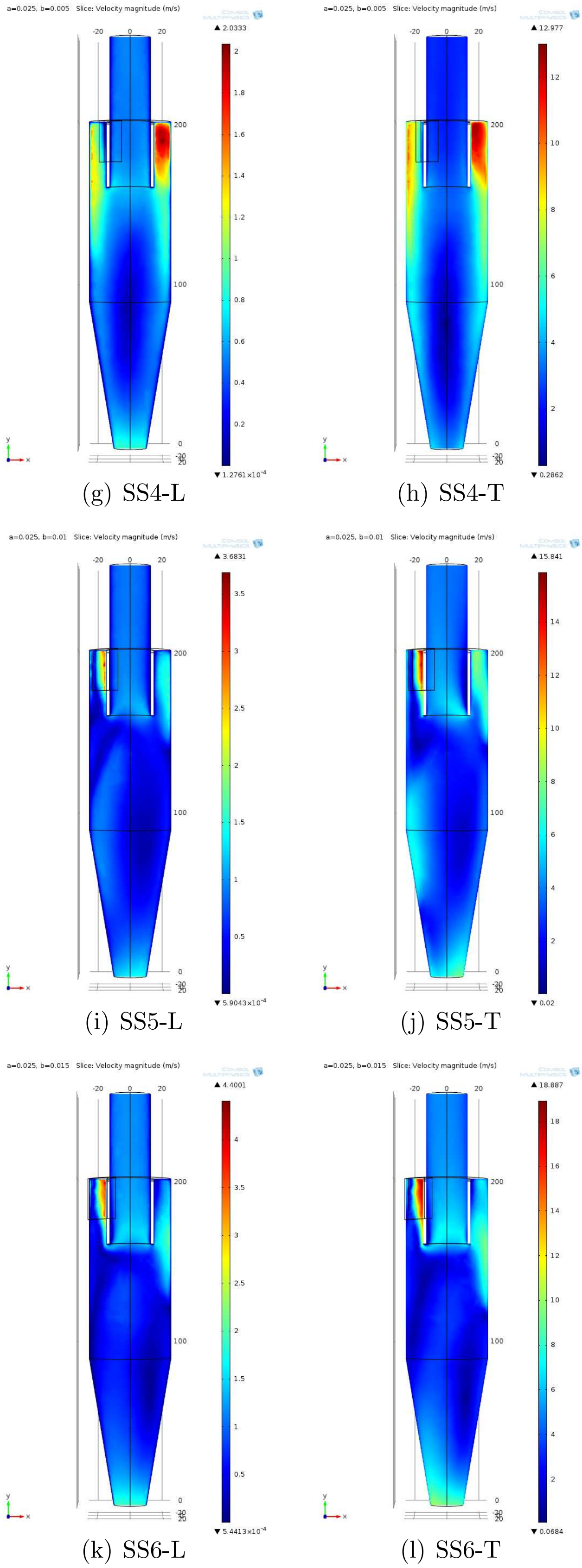
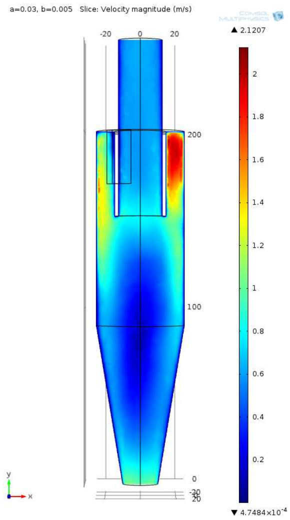
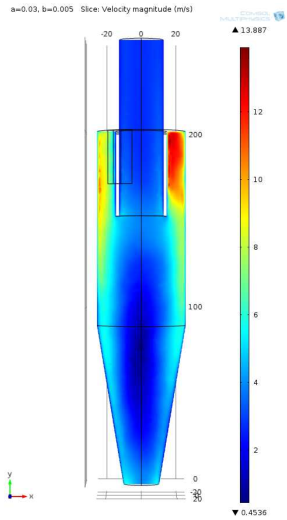


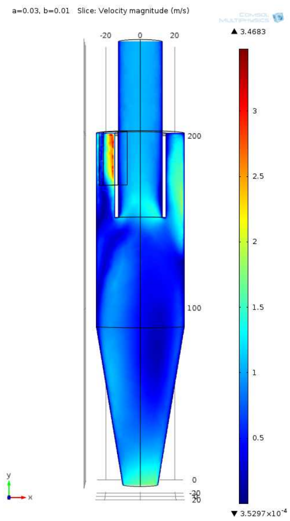
Figure 3.24. Single slot input-SS MODELS-Velocity profile in laminar(L) & turbulent(T) solvers (g-l).



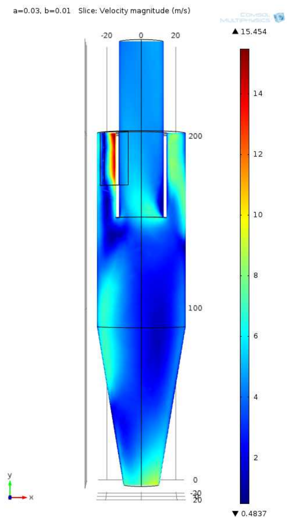
(m) SS7-L



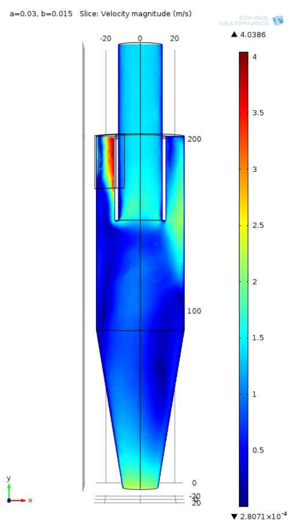
(n) SS7-T



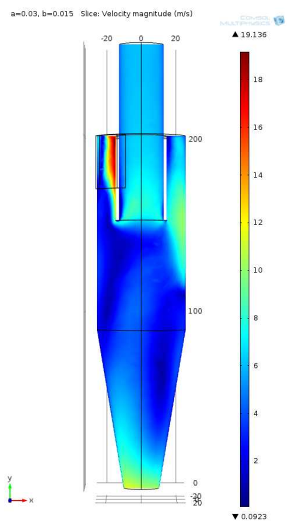
(o) SS8-L



(p) SS8-T

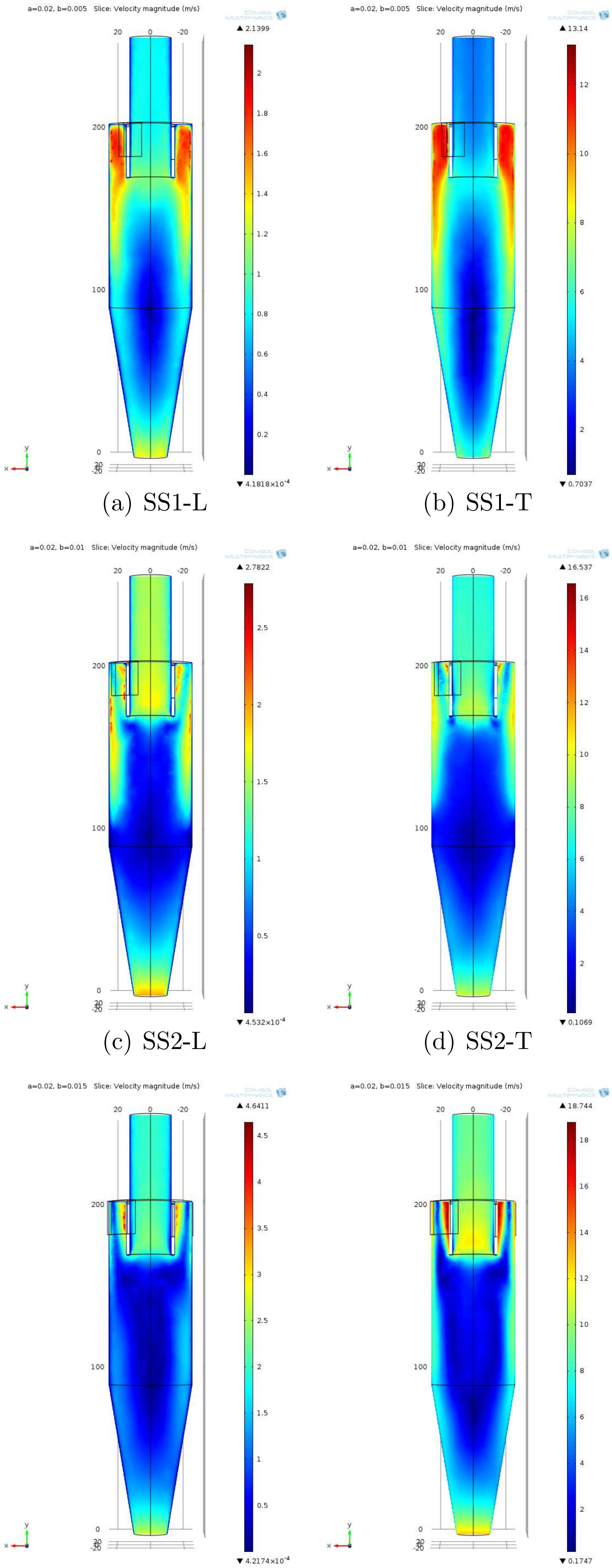


(q) SS9-L



(r) SS9-T

Figure 3.25. Single slot input-SS MODELS-Velocity profile in laminar(L) & turbulent(T) solvers (m-r).

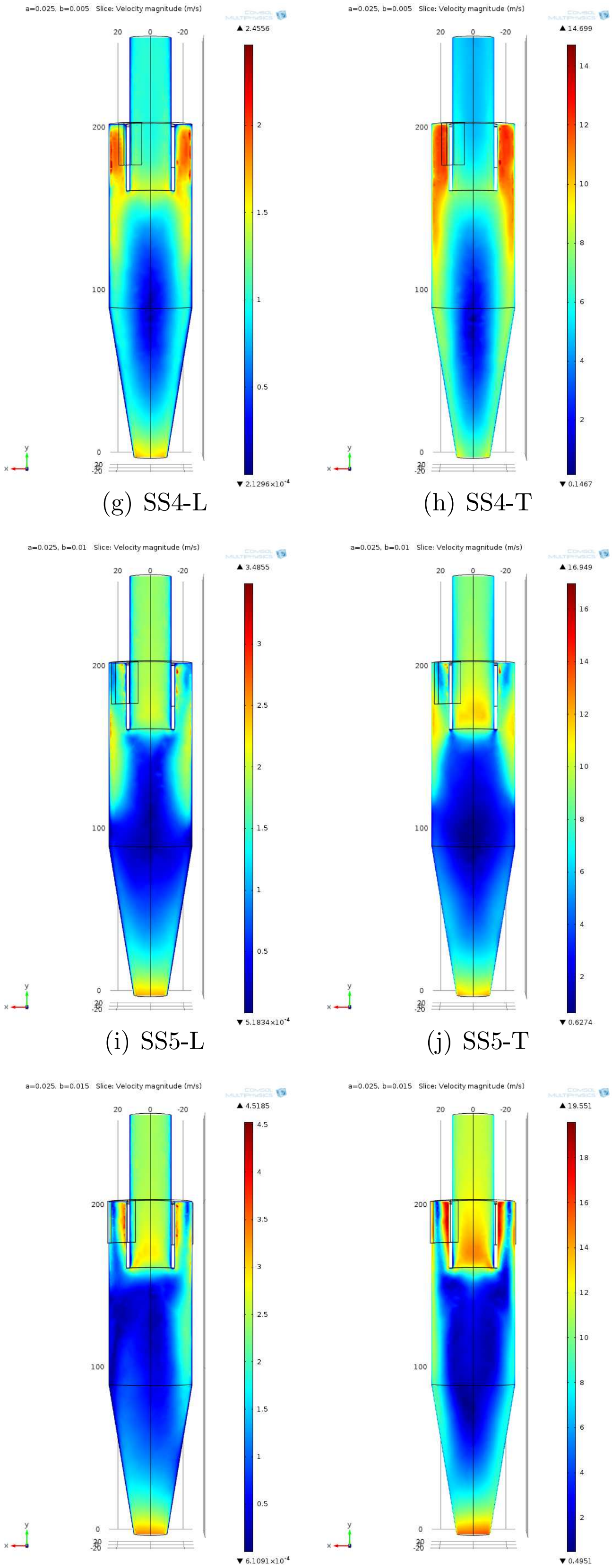


(a) SS1-L (b) SS1-T

(c) SS2-L (d) SS2-T

(e) SS3-L (f) SS3-T

Figure 3.26. Double slot inputs-SS MODELS-Velocity profile in laminar(L) & turbulent(T) solvers (a-f).

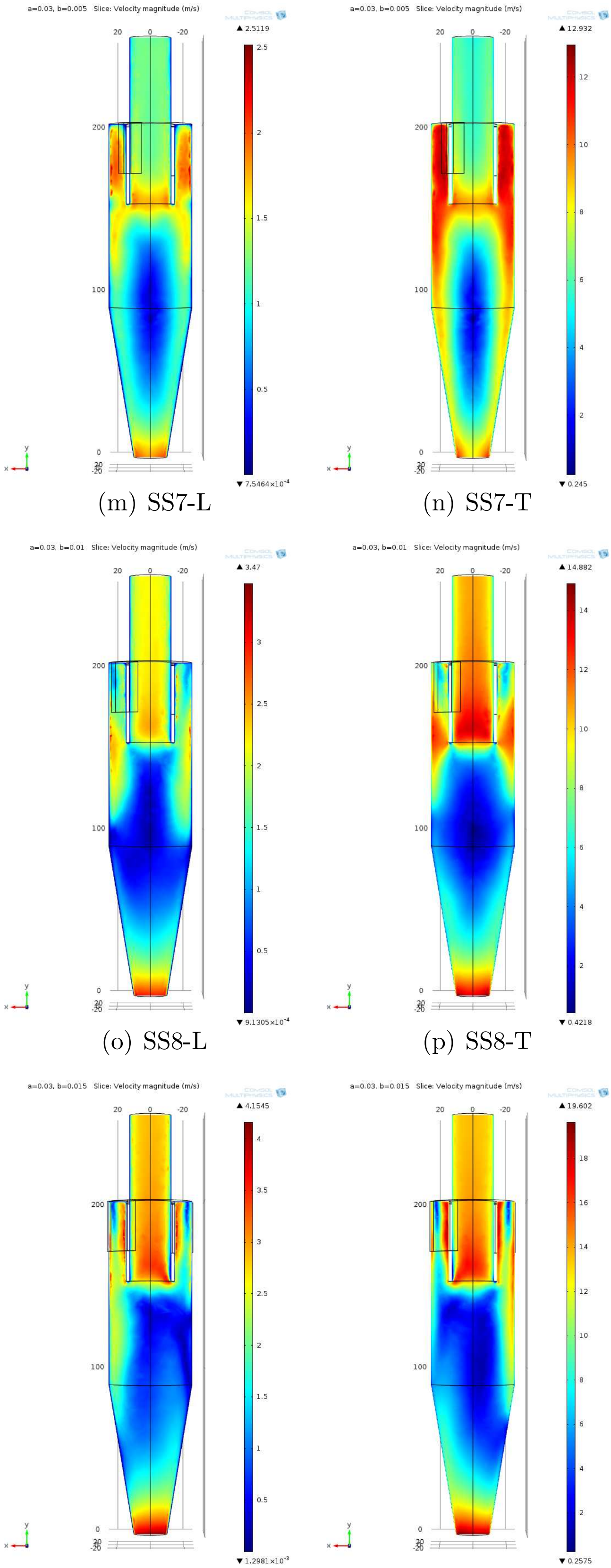


(g) SS4-L (h) SS4-T

(i) SS5-L (j) SS5-T

(k) SS6-L (l) SS6-T

Figure 3.27. Double slot inputs-SS MODELS-Velocity profile in laminar(L) & turbulent(T) solvers (g-l).



(m) SS7-L (n) SS7-T

(o) SS8-L (p) SS8-T

(q) SS9-L (r) SS9-T

Figure 3.28. Double slot inputs-SS MODELS-Velocity profile in laminar(L) & turbulent(T) solvers (m-r).

factors are drawn in line charts. The particle trajectory of the models is highlighted in Figures 3.29 and 3.30 for single and double slot cyclones using 2 m/s inlet velocity. The numbers of input particles are similar in all nine models and it is 100. The diameters of particles are varied over a range of 2 μm to 8 μm. ($d = 2, 4, 6, 8\mu m$).

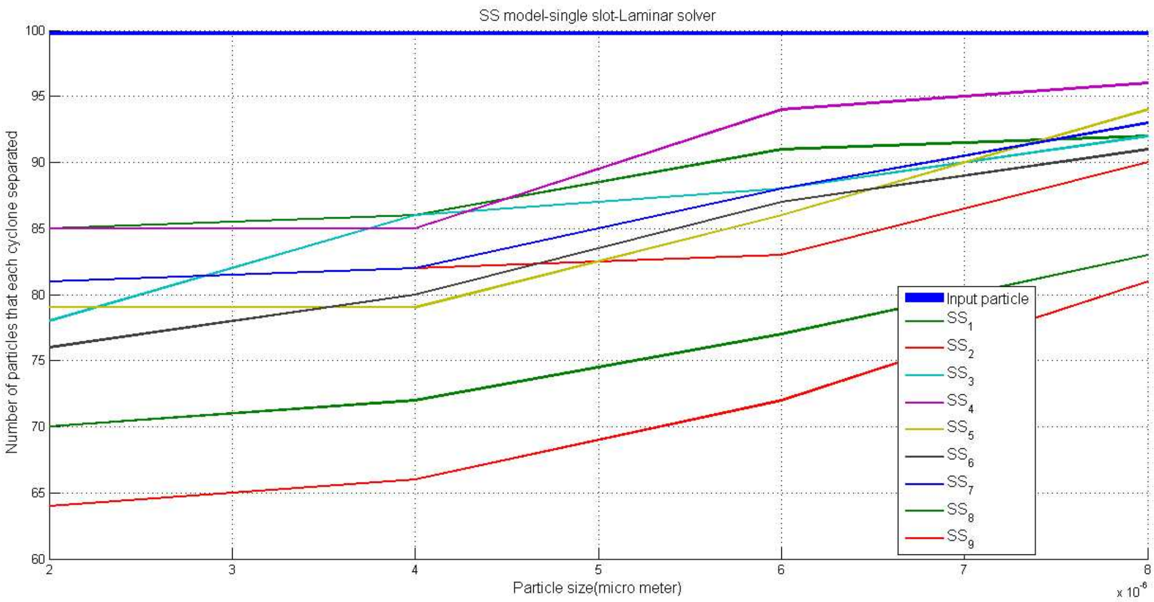


Figure 3.29. SS MODEL-Single slot-Low velocity.

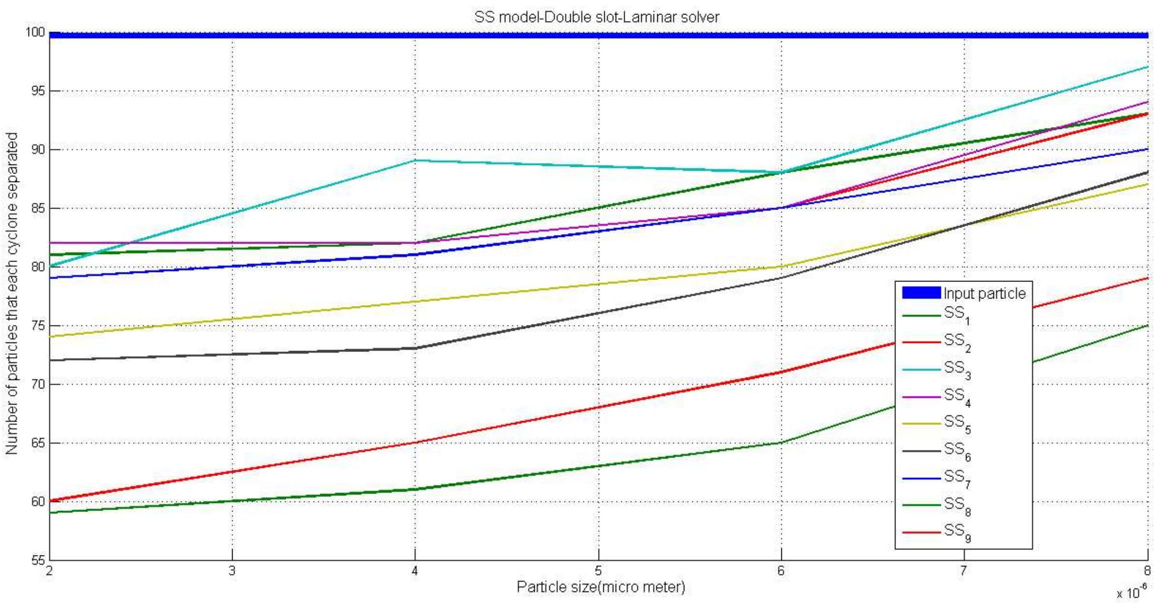


Figure 3.30. SS MODEL-Double slot-Low velocity.

Apparently, in these figures, it is effortless to distinguish which cyclone has the highest performance in removing particles. As depicted in the figures, there is a close agreement between single slot and double slot's simulation of particle evolution at the same condition. The blue line above is the number of input particles and the other lines with different colors beneath the blue line are related to other nine models. Comparing these nine models, it can be seen that SS4 has the most efficient cyclone in laminar flow with 2 m/s input velocity and one inlet slot with 90 percent separation efficiency. On the other hand, SS9 has the lowest efficiency with single slot with 70.75 percent separation efficiency. When it switches to double slot cyclone, the results have changed. SS8 with 65 percent separation efficiency is placed in the lowest rank and SS3 with 88.5 percent is on top. Indeed, as the graphs illustrate, the cyclones do not have a proper performance when the second slot with low speed entrance velocity is added. The slope of the curves shows the proportionality between effects of slots and velocity on the collection efficiency, and the order of the curve leads to a positive or negative influence.

Figures 3.31 and 3.32 illustrate the number of particles that each cyclone can catch when the inlet velocity rises to 10 m/s. As mentioned in the previous chapters, there is a direct relation between overall collection efficiency and flow rate or input velocity. In many studies, it is mentioned that increasing the input velocity will cause higher collection efficiency. Nonetheless, the separation efficiency of cyclones with double inlet is higher than the cyclones with single entrance and the same input velocity mostly. Exclusively, SS3 has the highest total collection efficiency with single slot. The effects of changing the inlet geometry demonstrate its influence on the overall collection efficiency in the cyclone by 95.75 %. On the other hand, when another inlet is added to the cyclones, SS3 is placed on the top with 96.5 % collection efficiency again. Meanwhile, SS7 with 84.25 % separation and SS9 with 87.5% collection efficiency have the lowest efficiency when single slot and double one is used.

Indeed, it is difficult to provide accurate figures for the precise geometry of the cyclone separator, due to the growth of the collection efficiency of particles; as far as, the working condition of cyclone is so important. The efficiency of each model is in a direct relation with input velocity. In SS models, with double entrance and input velocity increase from 2m/s to 10 m/s, the performance differences of these models increase from 5.75 % (SS7) to 18.75 % (SS9). Incidentally, the performance difference of SS5 and SS3 is 14 % and 9 %, respectively.

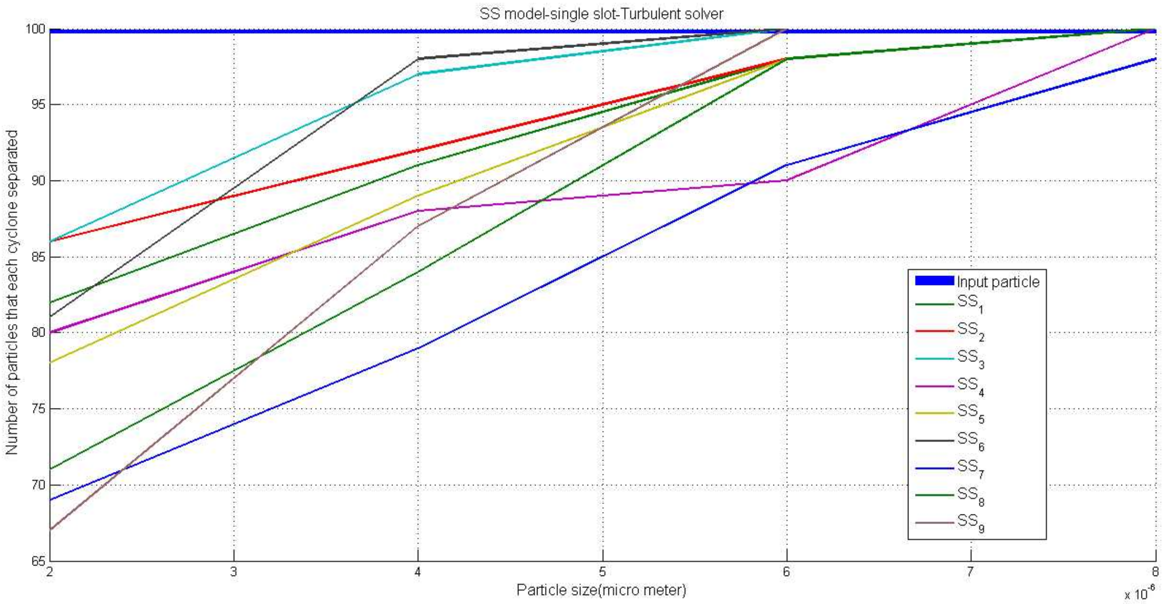


Figure 3.31. SS MODEL-Single slot-High velocity.

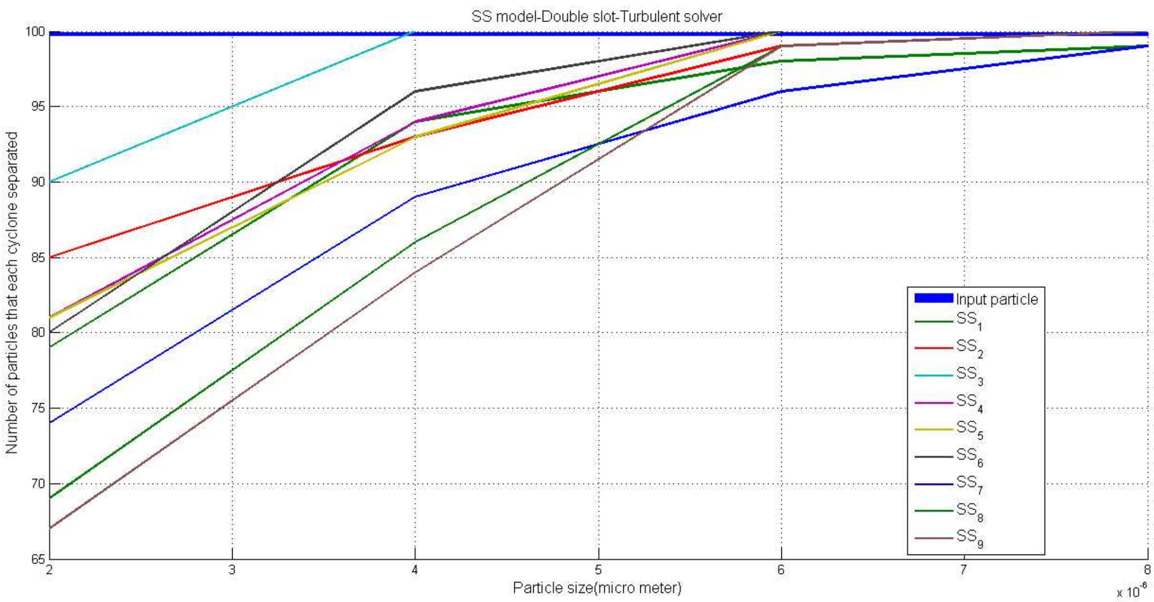


Figure 3.32. SS MODEL-Double slot-High velocity.

From another point of view, there is another comparison between cyclones which switch the number of slots from one to two when the inlet velocity is 10 m/s. The results are quite interesting. The minimum difference is for SS6 with 0.75 % and the maximum one is 5.25 % for SS7. In the same condition, SS5 has 2.25 % and SS3 has 1.75 % .

After analyzing the nine cyclones in COMSOL and comparing their results with Muschelknautz method, it can be seen that increasing the inlet velocity is more effective than adding the second slot to cyclones. Thanks to increasing the input velocity, the performance of cyclone boosts especially when the double slot input is used.

According to the results, each model can guide us to choose the correct model with high performance for collecting the particles and low pressure drop. Instead of choosing SS5 with one slot and 84.5 percent performance, we prefer to designate SS3 with double inlet and 96.5 percent overall collection efficiency. The comparison of two models shows that the inlet height of slots decreases 20 % and the inlet width increases 33.3 percent.

4. CONCLUSION

In this study, cyclonic separation is investigated using the Muschelknautz method (MM) and COMSOL multi- physics software. In both analysis techniques, the flow field is simulated at two input velocities $v_{in} = 2$ m/s and $v_{in} = 10$ m/s with different number of slots (single and double slot). There are two main case studies: the first one is made up four prominent models (Muschelknautz D type, Stairmand high efficiency, Lapple general purpose, Swift high efficiency), and the second is the SS model that contains 9 case with different inlet dimensions and vortex finder length geometry. The purpose of using these nine models is to optimize the collection efficiency of cyclone. The results obtained from both approaches are compared with each other, and a close agreement is achieved.

Furthermore, computational fluid dynamics (CFD) proposes a more accurate outcomes than MM especially in turbulent flow and in high input velocity. This technique is implemented to the particle trajectory module, considering an appropriate vision of collection efficiency of tested cyclones. In the first case study, Muschelknautz D type model shows a good overall collection efficiency. This model has lower average velocity in the top lid in comparison to the other models, in both single and double inlets cases. The velocities are about 0.4, 1.6 m/s in single slot and 0.97, 3.6 m/s with twin inlet in low and high intake velocity, respectively. According to the MM results, this model with one slot has a different cut-size and separation efficiency while intake velocity rises from 2 to 10 m/s. The evaluated data are $x_{50} = 4.69\ \mu m$, with $\eta = 92.18$ % in low speed, and $x_{50} = 1.32\ \mu m$, with $\eta = 99.89$ % in high speed. In addition, the streamlines are demonstrated; in both single and double slot, Muschelknautz D type model has symmetric vortex and a proper middle zone for changing the direction of gas stream and negative pressure side for helping more particle separation. Apart from predicting the collection efficiency with pressure drop and velocity, COMSOL has represented quite an effective approach to catch almost accurate outcomes in the particle trajectory. This notion has been illustrated in some figures in previous chapters. In the Muschelknautz D type model with low entrance speed, the average collection efficiency of cyclone has been decreased from 93.25 to 89.25 % when they choose double slot cyclone. On the other hand, in high speed intake gas flow in the same cyclone, the average separation efficiency has increased from 99.25 to 99.55 % with double slot cyclone.

One of the most important parameters in dealing with increasing or decreasing collection efficiency is changing inlet geometry and the number of slots. Different combinations of these two parameters have been studied to find the most efficient model.

For same input velocities, the average velocity in the top lid rises rapidly when inlet width or inlet height increases, in both single and double slots. Thus, the average Reynolds number in the top lid rises as the inlet width or inlet height increases too. Likewise, according to the MM, when inlet width develops, cut-size diameter, x_{50}, performance, η and solid loading, c_o diminish in low input velocity and single slot cyclone. It is better to mention that the cut-size and solid loading decreases dramatically when inlet width increases. On the other hand, as the inlet height and vortex finder length increase, the cut-size and efficiency decrease but solid loading increases.

In the middle region of the cyclone, there is a small zone in which the static pressure plays a crucial role for collection efficiency. According to the COMSOL results for single and double slot cyclones, when the inlet width increases, the static pressure varies between 245.07 % to 327.76 % in low velocity input. In high speed entrance, pressure fluctuation changes from 611.1 % to 249.8 % in one slot and two slot cyclones. Consequently, a good collection efficiency can be observed when the pressure drop diminishes inside the cyclone. Therefore, a decrease in the static pressure occurs when the inlet width decreases and the inlet velocity increases, when a second slot is added to the cyclone. Another way to control the pressure drop variation is to change the inlet height. Increasing the length of inlet causes a rise in static pressure from 118.89 % to 144.43% in single slot cyclone when increasing inlet velocity from 2 to 10 m/s in average. This is observed for double slot cyclones to vary between 133.15 % to 128.57 % in average, same as the condition that was mentioned before.

Apparently, it is not easy to determine which cyclone has a high collection efficiency. It is obvious that increasing the input velocity is a crucial key to develop the collection efficiency according to the previous studies, but there are many parameters that can influence the performance of this device. In a single slot cyclone with low speed gas flow, with an increasing inlet width, the separation efficiency decreases but when the inlet height and vortex finder length rise, the efficiency fluctuates. On the other hand, adding second slot to the cyclones changes the results completely. As **a** and **S** increase, the efficiency decreases sharply, but when **b** increases, the efficiency fluctuates. The important part is realizing the effect of adding a second slot at the high entrance velocity on the collection efficiency. In high input velocity (10 m/s) and one slot cyclone, the performance increases when **b** rises and decreases when **a** increases. In double slot cyclone, when **a** and **S** remain constant and **b** increases, the collection efficiency goes up, except in the largest size of **a**, the performance goes down. In conclusion, in comparison to nine models, SS4 has the most efficient cyclone, when the input velocity is low and cyclone has one slot. The separation efficiency is 90 %. On the other hand, single slot SS9 has the lowest efficiency among the other cyclones with 70.75 % separation efficiency. The results are changed, when double slot cyclones are used. SS8 with 65 % separation efficiency is in the lowest step and SS3 with 88.5 percent place on the top rank. Indeed, according to the results, the cyclones do not show expected performance when the second slot is added in low input velocity; but, in double slot cyclone with high input velocity, SS3 has maximum separation efficiency among the tested models. This amount is 96.5 %. In the same condition, the original model (SS5) has 93.5 % separation efficiency.

According to the results, to be able to choose the precise model and dimensions, we should follow some crucial steps. Choosing an appropriate inlet velocity and particle sizing are crucial boundary conditions, because some of the cyclone geometries work in a low inlet velocity with more efficiency than the others. Moreover, the cyclone has only one inlet; consequently, the flow should be asymmetrical. However, this asymmetry decreases the efficiency. The double slot cyclones have some advantages. It makes a symmetric flow pattern and diminishes the number of cyclones that are used inside pressure vessels. For that reason, many companies profitably use multi-cyclone with double input in pressure vessels. According to the previous researches, the geometrical parameters are related to each other, and a correct size has to be chosen based on the CFD and mathematical analyses.

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