SIMULATION AND VISUALIZATION OF GAS CENTRIFUGE DEVICE FOR ISOTOPE SEPARATION AND FUEL ENRICHMENT PROCESS

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ABSTRACT

SIMULATION AND VISUALIZATION OF GAS CENTRIFUGE DEVICE FOR ISOTOPE SEPARATION AND FUEL ENRICHMENT PROCESS

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In this thesis, the simple gas centrifuge theory was investigated under steady state conditions. This research is showed that the gas centrifuge improve possible isotope separation when it is applied some gas pairs. The rotation of centrifuge and the magnitude of the charge density have a major impact on the isotope separation to establish the steady state mole fraction profiles by gas centrifuge method. The effect of self-diffusion of the gaseous mixtures was indicated to be more important with low molecular weight gases than the high molecular weight gases. The separation is more increases as the difference between the molecular weights of gases increases such as UF_6 and SO_2-H_2. The necessary time to reach steady state pressure and mole concentration profiles is in the order of seconds, without any gas entering and exiting from the gas centrifuge machine. The separation of some gases such as SO_2-N_2, SO_2-H_2 and UF_6 have been studied with gas centrifuge method. The mole fractions of gases were investigated and calculated at any radius from center of centrifuge wall. The graphs of mole fractions were plotted and visualized during the simulation via graphical user interface which has been prepared for input data and to obtain output data as graph of mole fraction.

Keywords: Gas centrifuge, Isotope separation, Fuel enrichment, Simulation

ÖZET

İZOTOPLARI AYRIŞTIRMA VE YAKIT ZENGİNLEŞTİRME İŞLEMİ İÇİN GAZ SANTRIFUJ CİHAZI SİMÜLASYONU VE GÖRSELLEŞTİRİLMESİ

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Bu çalışmada gaz santrifüj teorisinin kararlı hal davranışı incelendi. Bu inceleme gaz santrifüj metodunun bazı gazlara uygulanması sonucu olası izotop ayrışmaların arttığını göstermektedir. Kararlı hal mol profili oluşturmak için santrifüjün dönme hızı ve yük yoğunluğunun gaz santrifüj metot ile ayrıştırma üzerinde büyük etkisi vardır. Gaz karışımların kendi kendine difüzyon etkisinin ağır molekül ağırlıklı gazlara nazaran düşük molekül ağırlıklı gazlarda daha önemli olduğu gösterilmiştir. Gazlar arasındaki molekül ağırlıkları farkı arttıkça, SO_2-H_2 ve UF_6 da olduğu gibi, ayrışma daha fazla olur. Gaz santrifüje hiçbir gaz giriş ve çıkışı olmaksızın mol ve basınç yoğunluğunun karalı hale ulaşma süresi saniye mertebesindedir. Bu tezde, SO_2-N_2, SO_2-H_2 ve UF_6 gazlarının santrifüj yöntem ile ayrışması çalışıldı. Gaz santrifüj metodu ile merkezden duvara herhangi bir boşlukta bu gazların mol yoğunlukları incelendi ve hesaplandı. Mol yoğunluklarının grafikleri çizildi ve çıkış verileri elde eden ve giriş verileri hazırlayan grafiksel kullanıcı arayüz sayesinde simülasyon görselleştirildi.

Anahtar kelimeler: Gaz santrifüj, İzotop ayrışması, Yakıt zenginleştirme, Simülasyon

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LIST OF SYMBOLS

S	The effort in SWU
P	Mass of product
W	Mass of waste
F	Mass of feed
X_w	Assay of the waste
X_P	Assay of the product
X_F	Assay of the feed
υ_L	Speed of light molecules
υ_H	Speed of heavy molecules
m_H	Mass of heavy molecules
m_L	Mass of light molecules
m_e	Mass of electron
v	electron velocity
q	Charge of electron
B	Magnetic field
ρ	Density
P	Pressure
G_c	Gravitational constant
MW	Molecular weight

ω	Peripheral speed
R_w	Wall radius
T	Temperature
IAEA	International Atom Energy Agency
GC	Gas Centrifuge
EMIS	Electromagnetic Isotope Separation
AVLIS	Atomic Vapor Laser Isotope Separation
MLIS	Molecular Laser Isotope Separation
UF_6	Uranium Hexaflouride
SWU	Separative Work Unit
GUI	Graphical User Intreface
CLI	Command Line Interface
CPU	Central Processing Unit

CHAPTER 1

GENERAL INTRODUCTION

Isotopes are the atoms having the same number of protons, but they have different number of neutrons. Isotope separation is the process of removing individual isotopes of an atom from other isotopes such as separating natural uranium into enriched and depleted uranium. This is very important process in the uranium fuel for nuclear power plants. Isotope separation is a significant operation for peaceful and armed forces nuclear science. Therefore, separation process is controlled for not produced weapons by an agency which called International Atom Energy Agency (IAEA).

The world has used currently three nuclear enrichment processes in operational. These processes are

- Gas centrifuge,
- Gaseous diffusion and
- Electromagnetic isotope separation (EMIS).

EMIS enrichment process is an inefficient process and canceled operation. Because electricity consumption is very large due to magnetic field and accelerations of electron in electromagnetic separation according to gaseous diffusion and gas centrifuge. Gaseous diffusion method currently accounts for 25 percent of whole world enriched uranium and is necessary more than 1400 stages to enrich uranium to a useful level. The gas centrifuge for isotope separation is playing an increasingly important role in the civilian nuclear fuel cycle. Gas centrifuge method currently accounts for 65 percent of whole world enriched uranium. There are some new and different methods for isotope separation and fuel enrichment processes such as laser isotope separation, nozzle separation but they are still experimental.

There are three isotopes in the natural uranium ore. Uranium is found as ^{238}U (99.2742%),^{235}U (0.7204%), and a very small amount of ^{234}U (0.0054%). ^{235}U is fissile material that is capable of undergoing fission after capturing low-energy thermal (slow) neutrons but ^{238}U is not fissile material. Therefore, one must separate ^{235}U from natural uranium. For large-scale enrichment, gaseous diffusion and gas centrifugation are used as two most common methods. In these enrichment processes, the gas flow rate of single enrichment component is not large. Therefore, a many enrichment device must be interconnected in parallel in enrichment plant. Also, since enough degree of enrichment may not be achieved in one enrichment device, enrichment machines must be connected together. This process is called cascaded. A cascade consists of separation units arranged in parallel that make up a stage. The stages are also connected in parallel. Each centrifuge has an input and two outputs that have light and heavy fractions. The input of each centrifuge consists of the output (waste) of the first centrifuge and the output (enrich) of the last stage. This produces a pure light fraction from the output (enrich) of the previous centrifuge and an almost pure heavy fraction from the output (waste) of the following centrifuge.

Uranium enrichment is a necessary component of the fuel cycle of light water reactors (LWR), high temperature reactors (HTR) and advanced gas-cooled reactors (AGR). When ^{235}U enriched to higher levels about 90 percent, it can be used as a nuclear explosive material in nuclear weapons. The gas centrifuge isotope separation or fuel enrichment device can also be used to enrich the natural gas for industrial use.

The purpose of this thesis is to observe isotope separation by gas centrifuge method and to simulate gas centrifuge device. The primary aim is to obtain information about isotope separation methods and especially to see performance of gas centrifuge method. Therefore, we studied to separate some gases with gas centrifuge method. These gases are SO_2-N_2, SO_2-H_2 and UF_6.

Chapter 2 was given general information about isotope separation and explained types of isotope separation methods. The properties and importance of gas centrifuge method that used enrichment uranium was examined in Chapter 3. The simple gas centrifuge theory was investigated under steady state behavior in Chapter 4. Mole fraction of these gases were investigated and calculated with gas centrifuge method and given with explanations for a steady state gas dynamics in this chapter.

The result of data produced by calculation are also used to graph of mole fractions while the simulation process. For this graph of mole fractions calculation a graphical user interface program was prepared and added in Chapter 5 with the coding details.

CHAPTER 2

ISOTOPE SEPARATION

2.1 Introduction

Isotopes are types of a specific chemical element. Isotopes of an element are same number of protons, but they have differed number of neutrons. The term isotope is formed from the Greek roots equal (isos) and place (topos) and called same place because of the same position on the periodic table and was suggested to Soddy who is an English radiochemistry in 1914 by Margaret Todd [1]. The number of protons in atoms identifies an element, but mass number is not the same for two isotopes.

Isotope separation is the process of removing individual isotope of an atom from other isotopes, separating natural uranium into enriched and depleted uranium. This is very important process in the uranium fuel for nuclear power plants. Isotope separation is a significant operation for peaceful and armed forces nuclear science. Therefore, separation process is controlled for not produced weapons by an agency which called International Atom Energy Agency (IAEA) [2].

Isotope separation process carried out commercially in three different type's techniques [3]. First of these techniques based on the small differences produced by different atomic weights in chemical composition, second of these techniques based on the isotope atomic weight and third of these techniques based on properties not directly connected to atomic weight but connected to nuclear resonances. Two of these techniques are used commercially for nuclear fuel enrichment process but the third type is in experimental stage and has no many publications. Therefore, it is commonly easier to separate isotopes with higher mass differences. For instance, mass of hydrogen has half the mass of deuterium and it is easier than to separate ^{235}U from^{238}U.

Up to this time, only three elements have occurred for commercial isotope separation technique. In each case, rare of an element has been concentrated from most common isotopes for use in nuclear science. These three elements are uranium, hydrogen and lithium-6. Uranium elements have been separated for nuclear reactor fuel and weapons. Hydrogen has been concentrated to ^2H for use as a moderator in reactor. ^6Li isotope has been separated for use in thermonuclear weapons [4].

2.2 Form of Uranium Hexafluoride (UF_6)

Uranium hexafluoride is a radioactive material and chemical compound made up from six atoms F (fluorine) and one atom U (uranium). It used during the uranium enrichment process. It can be a gas, liquid, or solid with suitable range of temperature and pressure. As shown in Figure 2.1, solid uranium hexafluoride is dense, white and crystalline matter that looks like salt. UF_6 has phase diagram as shown Figure 2.2 [5].

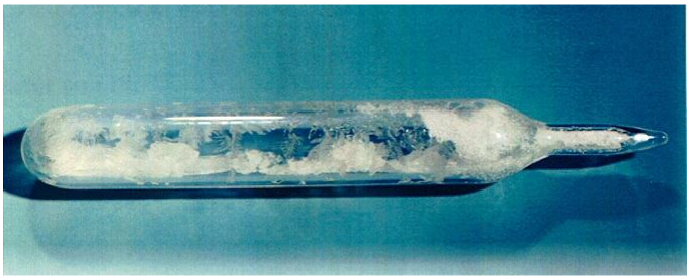


Figure 2.1 Solid Uranium Hexafluoride (UF_6) [6].

UF_6 does not react with O, N, CO_2 or dry air, but it does react with H_2O or H_2O vapor. UF_6 is always protected in leak tight containers equipment. When UF_6 react with water, such as H_2O vapor in the air, forming corrosive HF and a uranium-fluoride compound called uranyl fluoride (UO_2F_2).

In the first step of UF_6 production, uranium ore is mined and sent to convert uranium oxide. The uranium oxide is then sent to a UF_6 production plant. In the drying operation, uranium oxide concentrates are heated more than enough to remove some impurities, then gathered and grinded [8].

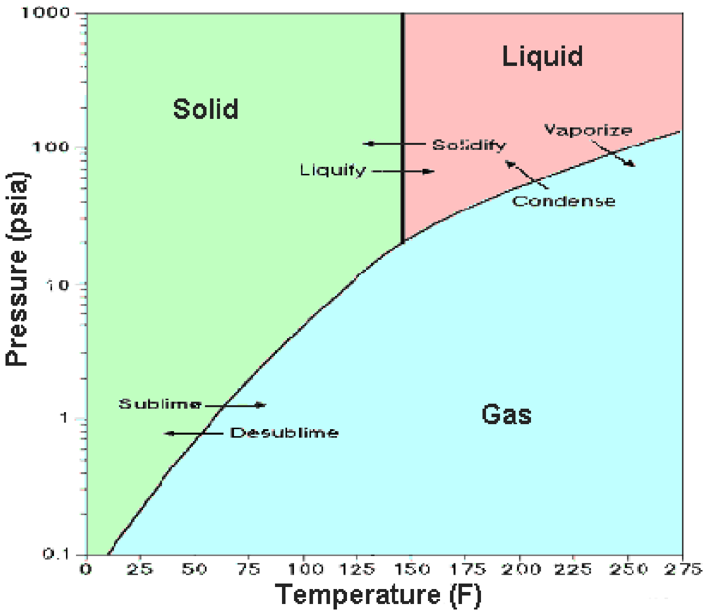


Figure 2.2 Uranium hexafluoride phase diagram [7].

For the moist operation, the uranium oxide is dissolved in nitric acid (HNO_3). The resulting solution of uranyl nitrate UO_2 $(NO_3)_2$. H_6O_2 is fed into a countercurrent solvent extraction process, using tributyl phosphate dissolved in kerosene or dodecane. The uranium is collected by the organic extracting, from which it can be washed out by dilute nitric acid solution and then concentrated by evaporation. The solution is then calcined in a fluidized bed reactor to produce UO_3 or UO_2 if heated sufficiently.

Purified U_3O_8 from the dry process and purified uranium oxide UO_3 from the wet process are then reduced in a kiln by hydrogen to UO_2:

$$U_3O_8 + 2H_2 ===> 3UO_2 + 2H_2O \qquad \Delta H = -109 \text{ kJ/mole} \qquad (2.1)$$

or

$$UO_3 + H_2 ===> UO_2 + H_2O \qquad \Delta H = -109 \text{ kJ/mole} \qquad (2.2)$$

This reduced oxide is then reacted in another kiln with HF to form uranium UF_4, though in some places this is made with aqueous HF by a wet process:

$$UO_2 + 4HF ===> UF_4 + 2H_2O \quad \Delta H = -176 \text{ kJ/mole} \qquad (2.3)$$

The tetra fluoride is then fed into a fluidised bed reactor or flame tower with gaseous fluorine to produce uranium hexafluoride, UF_6. Hexafluoride ("hex") is condensed and stored.

$$UF_4 + F_2 ===> UF_6 \tag{2.4}$$

Uranium Hexafluoride is formed at the end of these processes.

2.3 Separative Work Unit (SWU)

Separative work is the amount of separation done by an isotope separation process. It is a function of the concentrations of the feedstock, the enriched output, and the depleted tailings. Separative work is expressed in units which are so calculated as to be proportional to the total input (energy / machine operation time) and to the mass processed. Separative work is not energy. The same amount of separative work will require different amounts of energy depending on the efficiency of the separation technology. Separative work is measured in Separative work units SWU or kg SW [9, 10].

- 1 SWU = 1 kg SW = 1 kg UTA
- 1 kSWU = 1 tSW = 1 t UTA
- 1 MSWU = 1 ktSW = 1 kt UTA

where UTA is the German Urantrennarbeit and separative work unit is a unit that used to determine the magnitude of the achievement needed to separate two isotopes of an element, so that the proportion of one isotope is increased in one of the resulting products. The dimension of the SWU is mass. Although the SWU is often described as a unit of energy, it is not, as the table below shows.

Table 2.1 Comparison of energy per SWU with isotope separation [11].

Process	Energy used per SWU
Gaseous Diffusion	2400 kilowatt-hours (8600 mega joules)
Gas Centrifuge	50 kWh (180 MJ)

Exact calculation of SWUs includes differential equations. The equation below can be used.

$$S = P(2x_P - 1)\ln\frac{x_P}{1-x_P} + W(2x_W - 1)\ln\frac{x_W}{1-x_W} - F(2x_F - 1)\ln\frac{x_F}{1-x_F} \tag{2.5}$$

where S is the effort in SWU's, P is the mass of the product, W is the mass of the waste, F is the mass of the feed, x_W assay of the waste, x_P assay of the product, x_F assay of the feed.

2.4 Techniques of Isotope Separation

2.4.1 Gaseous Diffusion Separation

Isotope separation process make an alter in the amount of molecules of the gas mixture. Gaseous diffusion process utilizes molecular diffusion to separate a gas from mixture of two gases [4, 12]. This process is found on the viewing that the lighter molecules travel quickly than the heavier molecules. The separation process can be defined on the simple of molecules velocities. The heavy (H) and light (L) molecules are same average kinetic energies in the gas mixture, but since the masses and speeds are not same. Difference in speeds is rate of the square root of the mass ratio.

$$\frac{\vartheta_L}{\vartheta_H} = \sqrt{\frac{m_H}{m_L}} \tag{2.6}$$

where $\vartheta_L, \vartheta_H, m_H, m_L$ are the respective speeds and masses.

The lighter molecules hit the container walls more probability than heavier molecules. If a part of the cylindrical container consists of a penetrable substance having holes sufficiency to allow private gas molecules. However, holes not so large that a mass flow-through of the gas can take place. Light molecules will go out of the container than heavy molecules. The gas leave out the container is therefore enriched in the lighter molecules, whereas the remaining gas is comparably depleted. This fact is illustrated in Fig. 2.3, which indicate the actual type of container, barrier configuration, and piping links utilized in some gaseous diffusion plants. In the figure, diffuser is a single container.

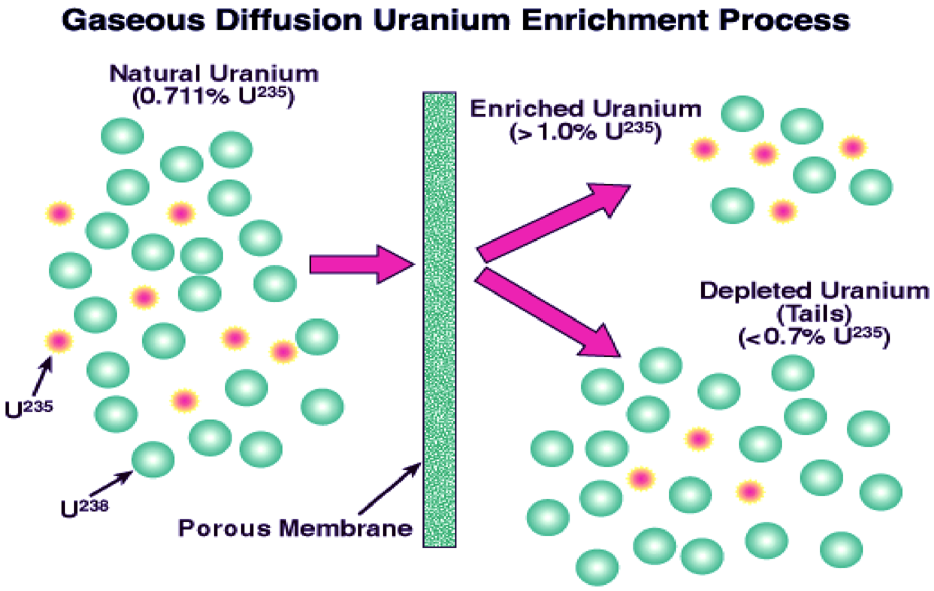


Figure 2.3 Schematic of gaseous diffusion separation technique [14].

Uranium is in solid phase at the room temperature, and the isotope enrichment process of uranium is accomplished using uranium hexafluoride, UF_6. Although this composition is a solid at room temperature, it is passed easily gas state. However, this requires that all components of a diffusion plant be keep up an suitable temperature to confirm that the UF_6 stays on gaseous form.

Despite uranium hexafluoride is a steady compound, it is greatly reactive with water and corrosive to more metals. As a result, interior gaseous pathways must be manufactured from nickel or austenitic stainless steel and the full system must be leak tight. Despite its disagreeable characteristics, uranium hexafluoride is the only compound of uranium sufficiently vaporizing to be used in the gas diffusion process [13].

Fluorine only consists of the single isotope^{19}F. The difference in molecular weights of UF_6 is only due to the difference in molecular weights of the uranium isotopes. However, the molecular weights of $^{235}UF_6$ and $^{238}UF_6$ are nearly same; therefore separation of the $^{235}UF_6$ and $^{238}UF_6$ is very little by a single pass through a diffuser. It is essential to connect a more many diffusers together in an order of stages. Outputs use at each stage as the inputs for two next to stages. Cascade is an order of stages. In practice, gaseous diffusion cascades require thousands of stages relying on the product enrichment [15].

Separation factor r is a quantity depending on impressiveness of an isotope separation process [4]. If we supply gas molecule at one abundance ratio *R*, the ratio *R* on the low-pressure position of the barrier is given by

$$R' = rR. \tag{2.7}$$

If only a very small amount of gas is permitted to diffuse through the barrier, r is given by

$$r = \sqrt{\frac{\mathrm{m_H}}{\mathrm{m_L}}} = \sqrt{\frac{352}{349}} = 1.00430 \tag{2.8}$$

The amount of isotope separation is very little. By processing the gas in a series of s stages and a separation factor, the abundance ratio is increased by a factor r^s. If R_f and R_p refer to feed and product, respectively,

$$R_p = r^s R_f \tag{2.9}$$

Gaseous diffusion plant is very expensive technology which is the order of a billion dollars, because of the size and number of components like separators, pumps, valves, and controls. However, diffusion process is basically simple. A few operating personal is necessary to working at the diffusion plant. The electrical power is consumed to principal operating cost to provide the pressure differences and perform work on the gas [16].

The gas molecules must be compressed the diffuser at each stage for a loss in pressure. Gas molecules heated by compression, so gas molecules must be cooled before coming the diffuser. Gas diffusion plants consume enormous electric because of requirements for pumping and cooling. For example, a plant capacity of 10 million SWU/yr requires about 2,700 MW of electrical power. In the United States, the diffusion plants of the Department of Energy make it the nation's single largest user of electricity [13]. The first large gaseous diffusion separation method of uranium isotopes was achieved by the United States plants at Oak Ridge Laboratories [17 - 19].

Isotope separation with gaseous diffusion process is about 25% of world enrichment capacity at present [20]. Although they have verified reliable and durable, most gaseous diffusion plants are closed end of its technique. Gaseous diffusion plants replacing with centrifuge enrichment technology.

2.4.2 Laser Isotope Separation

Laser isotope separation is completely different and new technique for separating uranium [21, 22]. Initially, this method was developed in the 1970s in an accommodative program between Lawrence Livermore National Laboratory and Oak Ridge National Laboratory. Different isotopes of the same element have different electronic energies. Therefore isotopes absorb dissimilar colors of laser light. Uranium have two isotope which ^{238}U and^{235}U. Laser isotope separation is based on absorption of laser light and ionized the uranium isotope.

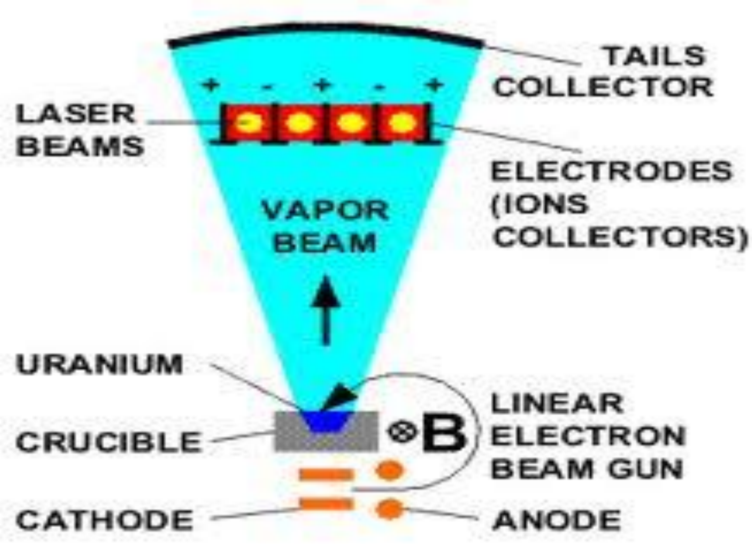


Figure 2.4 Laser isotope separation system [23].

Atoms have a ground and excited state. They live in ground state normally, but atoms can be replacing in excited state by absorption of suitable amounts of light energy. The excited states of atoms are dissimilar form of electrons, but molecules can go up different rotational or vibrational energies of molecular structure. In either case, electromagnetic radiations happen in the same method. If the energy of coming radiation does not match to potential transition between energy state, absorption happen very little. When the coming energy matches a potential transition, remarkable energy absorption may result. This resonance absorption is for excitation resonance in ^{235}U and ^{238}U at about 5,027 angstroms (1 angstroms=10^{-10} m), the wavelength of green light, incident photon energy is 2.4 eV.

In general, the laser separation have three systems, which are the

- optical systems
- laser systems
- separation module system.

Tunable lasers can be evolved to a greatly monochromatic radiation which has light of a single color. These lasers can be ionized a specific isotopic type, but other isotopic species not effect. The ionized type is then chemically or physically changed and the material is to be separated [24].

Laser isotope separation divided into two methods depending on the material used. These methods are

- Atomic Vapor Laser Isotope Separation (AVLIS)
- Molecular Laser Isotope Separation (MLIS)

2.4.2.1 Atomic Vapor Laser Isotope Separation(AVLIS)

Feed material of AVLIS is uranium-iron (U-Fe) metal alloy [25]. In AVLIS used the dye lasers can be tuned only ^{235}U atoms and it absorb the laser light. When the ^{235}U atom absorbs the laser light, its electrons are excited to a higher energy state. ^{235}U atom will emit an electron and happen a positively ion with absorption of adequate energy. The ^{235}U ions may be changed way by an electrostatic field. ^{235}U separated from ^{238}U and collected in the product collector. ^{238}U atoms remain neutral and are deposited on a tails collector.

There is no any currently operating commercial system with laser separation uranium enrichment plants in the world. The AVLIS process comparable with gas centrifuges process because of high energy efficiency, high separation factor, and low volume of radioactive waste.

2.4.2.2 Molecular Laser Isotope Separation(MLIS)

Molecular Laser Isotope Separation used UF_6 as feed materials [23]. This method is like the AVLIS. However, there is some difference which used UF_6 gas is mixed with an appropriate carrier gas which permits the molecules to hold in the gaseous state. In either case, Molecular separations have some advantage over AVLIS. Molecular LIS is advantage due to low energy consumption and use of uranium hexafluoride. MLIS was designed in 1961 at the Los Alamos National Laboratory [26].

2.4.3 Nozzle Isotope Separation

Nozzle separation process was developed by E.W. Becker and associates at the Karlsruhe Nuclear Research Center in Germany [27, 28]. UF_6 used with carrier gas hydrogen or helium at Nozzle process. This process based on diffusion driven by pressure difference, as does the gas centrifuge but not rotating centrifuge.

UF_6 is compressed with a carrier gas in order to increase the velocity of the gas stream into curved or convex tube and then guided along a curved wall at very high velocity. While gas molecules passing through the curved surface of the tube, they remain subject to central acceleration inversely proportional to the radius of curvature of the surface. Therefore, with relatively heavy $^{238}UF_6$ molecules thrown towards the more outer radius. In reversely, with relatively lighter $^{235}UF_6$ thrown towards the closer to the center of curvature. As a result, between the layers occur a difference and $^{238}UF_6$ seperated from$^{235}UF_6$. This layers cut by a planar knife at tube exit and directed to different pockets. This process is shown in Figure 2.4.

As nozzle shape improved in Germany, eddy tube developed in South Africa. At South Africa uranium hexafluoride enriched percent 3-5% for nuclear plant fuel and enriched percent 80-93% for nuclear plant fuel and enriched percent 80-93% for nuclear weapons production [30]. This process abandoned because of high consumption electric energy to compress the UF_6 and carrier gas mixture. And also operation of an aerodynamic separations plant generated a large amount of heat, therefore requires large amounts of coolants.

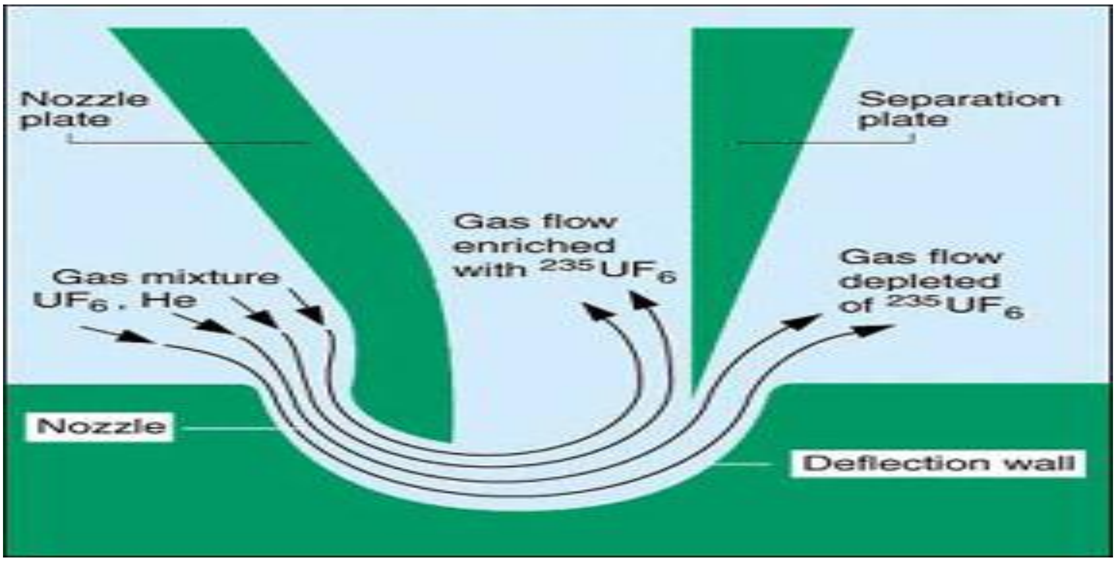


Figure 2.5 Schematically representation of nozzle isotope separation technique [29].

2.4.4 Electromagnetic Isotope Separation

Electromagnetic Isotope Separation method is same the principle of the mass spectrometer. This process was one of the earliest successful enrichment techniques. The EMIS method is based on the charged particle will follow a circular path of radius when applying magnetic field [4].

Different weights of ions with same kinetic energy make a circular motion in different radii when they enter a magnetic field perpendicular to aspect of movement. The heavy particles travel in curve of larger radius than the lighter particles. As shown in Figure 2.6.

The distance between the points is proportional to the difference in the square roots of the masses. The formula of distance is given by

$$r = \frac{m_e v}{qB} \tag{2.10}$$

Where m_e , v, q and B are mass of electron, speed of electron, charge of electron and magnetic field of intensity respectively.

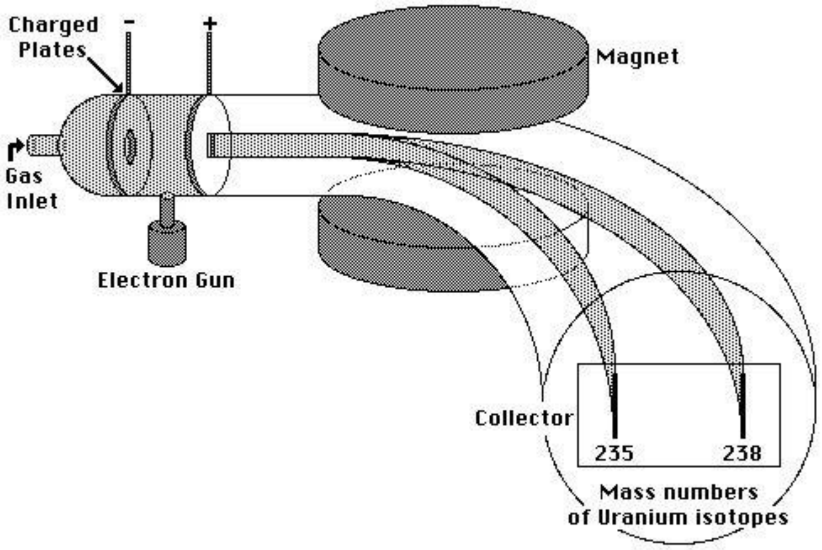


Figure 2.6 Electromagnetic isotope separation [30].

One of the advantages of the electromagnetic process can be obtained in one machine. However, electricity consumption is very large due to magnetic field and accelerated of electron in electromagnetic separation according to gaseous diffusion and gas centrifuge.

CHAPTER 3

GAS CENTRIFUGE

3.1 Introduction to Gas Centrifuge

A gas centrifuge is a device that separating isotopes of gaseous isotopes such as uranium in the form of UF_6. Also it called the ultra-centrifuge because of the very high speeds included. The device consists of a long, thin, vertical cylinder or rotor that made of material with high strength-to-density ratio. Centrifuges based on the centrifugal force moved molecules so that particles of different masses are physically separated [31].

The main subsystems of the centrifuge device are,

- rotor and end caps
- electric motor and power supply (frequency changer)
- vacuum system and casing
- top and bottom bearing/suspension system
- center post, scoops and baffles

In the gas centrifuge method, gaseous form of UF_6 is placed in an appropriate container or rotor and UF_6 rotated at very high speed shown in Figure 3.1. The gas rotating inside the cylinder is subject to centrifugal acceleration thousands of times greater than gravity [31, 32]. This makes the pressure at the outer radius of the cylinder millions of times greater than at the center. After this causes the relative abundance of the heavier isotope to be appreciably greater at the outer radius than at the center, whereas the lighter isotope accumulates relatively nearer the center. By inducing countercurrent flow between the U^{238}-depleted stream near the outer radius and the U^{235}-enriched stream near the axis, the difference in composition between the top and bottom can be made much greater than between the two streams at one elevation. Three general methods have been used for inducing countercurrent flow:

- by the system of internal scoops and baffles shown in Figure 3.1
- by convection currents set up by heating one end and cooling the other or establishing a temperature gradient along the wall
- by flow induced by pumps external to the machine

The last gives greater operating flexibility, but is much more complex mechanically. The gas centrifuge is most economical method than the other isotope separation techniques. They are the most widespread used technology today for isotope separation.

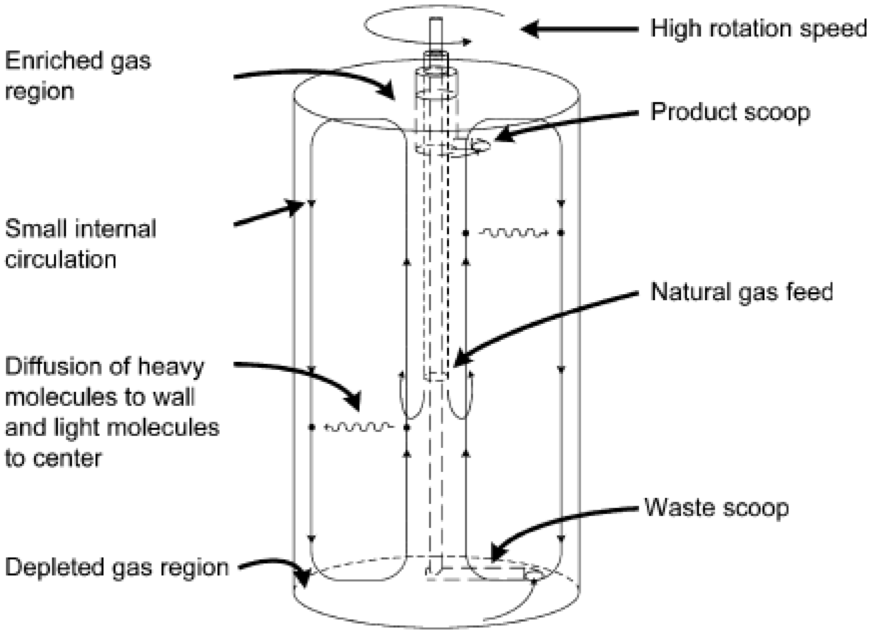


Figure 3.1 Countercurrent gas centrifuge with internal circulation [33].

3.2 History of Gas Centrifuge

The process of separating isotopes in a gas centrifuge was first recommended by Lindemann and Aston in 1919 [3]. The first successful use of gas centrifuge method was developed vacuum ultracentrifuges with the high peripheral speed needed for measurable isotope separation by Beams [34]. It was applied to separation of the isotopes of chlorine in carbon chloride (CCl) and other elements in 1938. In 1939, Urey suggested use of countercurrent flow to multiply single-stage enrichment by heating the bottom of the rotor and cooling the top [35]. The system of inner scoops and baffles was an important simplification introduced by Zippe [36]. Bramley, Brewer, Martin and Kuhn proposed alternative thermal convective means of internal circulation in 1940 [37]. The first reported enrichment of U^{235} by the gas centrifuge was obtained by Beams at the University of Virginia and co-workers in 1941, when 1.2 g of enriched uranium in U^{235} by 4 percent was obtained. Development of larger machines was supported by Westinghouse Electric Company with separation performance measurements under administrator of E. V. Murphree [31]. The largest centrifuge tested on UF_6 consisted of an alloy of aluminum tube 18.29 cm in internal diameter, 1.27 cm thick and 335.3 cm long. When operated at a peripheral speed of 206 m/s, a separative capacity around 1 kg SWU/year was obtained [38]. When the success of the gaseous diffusion process was demonstrated, this centrifuge work was terminated. Likewise, it was rejected pending World War II because materials that would resist high rotation speed were not obtainable and it gave large power losses. The German engineer G. Zippe who was devised the simple method of inducing counter flow by internal scoops and baffles during World War II. After the war Zippe continued his work with Beams at the University of Virginia from 1958 to 1960. The highest separative capacity there reported was 0.3 kg SWU/year for a rotor 7.41 cm in diameter and 30.2 cm long run at a peripheral speed of 350 m/s. In the 1960s, when the gas centrifuge began to come into view competitive for large-scale uranium enrichment and the nations then mainly responsible for its development, the United States, Great Britain, the Netherlands, and West Germany, agreed to place security restrictions on description of the technology [31].

3.3 Gas Centrifuge Materials

Gas centrifuge devices was abandoned during World War II due to materials were not available withstand high rotation speeds. However, developments of technology since have made centrifuges economical and practical. So materials very important at gas centrifuge devices.

The gas centrifuge devices consists of a cylindrical chamber or rotor turning at very high velocity in a vacuum in Figure 3.2.

Rotor is under large rotation forces because of rotational speed 100000 cycles per min. Material of rotor is necessary light and resistant [13, 31]. On the other hand, direct contact surfaces with UF_6 vapor must be made of materials resistant to oxidation of UF_6 vapor. Rotor rolled in space within the protective container to minimize friction losses. Since the rotation axis seated upper bearing is magnetic, rotor axis is in contact with only the lower bearing and rotor is spinning on a single point of contact that like needle tip [39]. Lower bearing and contained suspension is important. If rotor cylinder is turns very long and very fast, enrichment capacity of centrifuge unit is so higher. When cylindrical rotor returned at high speed, longitudinal oscillations consist of rotor. So lower bearing is necessary absorption oscillations and durable against to forces. The quality of the magnetic field that provides rotation of the rotor is important for stability. Frequency of the motor that returns rotor is 600 Hz or higher. Because, the speed of rotation rotor is directly proportional to frequency of rotor.

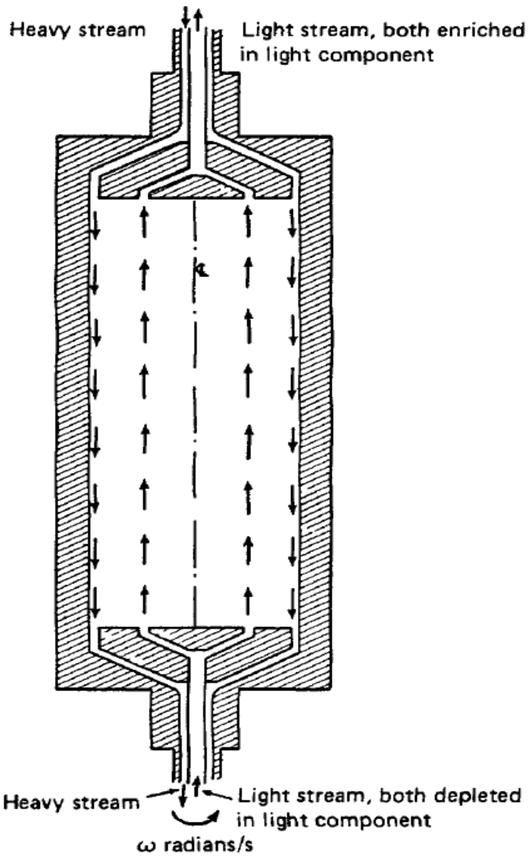


Figure 3.2 Countercurrent Gas Centrifuge with externally pumped streams [31].

Aluminum or Titanium was used as rotor material [39]. Martensitic steels are a special type alloy of stainless steel. They were used in rotor material after the 1960s. Martensitic stainless steels are consisted of low carbon steel, composition of Fe, 12%

Cr and 0.12% C. Martensitic steels can be hardened and tempered. Although they give great hardness material, it is easily processable and durable to oxidation and crack. They are a class of special low-carbon steel. Therefore, Martensitic stainless steel is now used as rotor material of gas centrifuge devices.

3.4 Cascade System

The gas flow rate of single centrifuge is not large. Therefore, a many centrifuge device must be interconnected in parallel in enrichment plant. Since enough degree of enrichment may not be achieved in one centrifuge, centrifuge machines must be connected together as shown in Figure 3.3. This process is called cascade.

A cascade consists of separation units arranged in parallel that make up a stage. Stages are connected in parallel. Each centrifuge has an input and two outputs that have light and heavy fractions. The input of each centrifuge consists of the output (waste) of the first centrifuge and the output (enrich) of the last stage. This produces a pure light fraction from the output (enrich) of the previous centrifuge and an almost pure heavy fraction from the output (waste) of the following centrifuge.

The external variables of the cascade are the feed flowing at a rate of F and containing x_F of the desired isotope, the product (or heads) flowing at a rate of P and containing x_P of the desired isotope and the waste (or tails) flowing at a rate of W and having a composition of x_W.

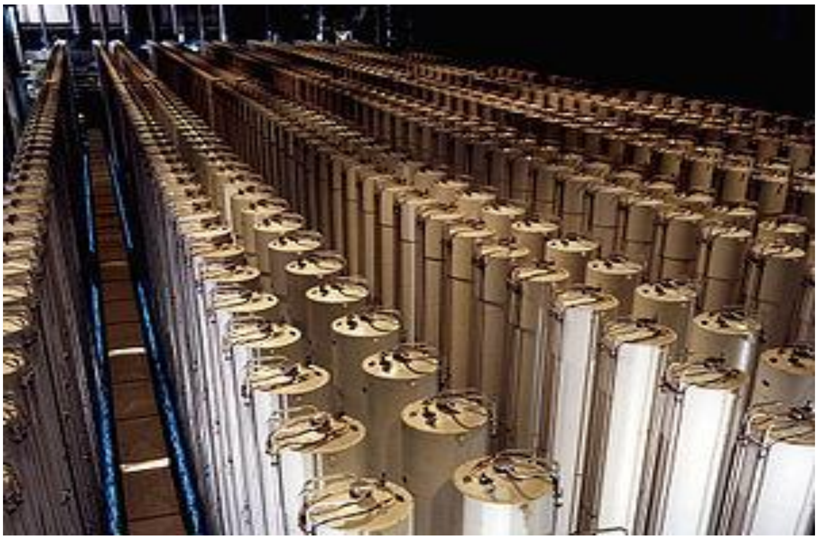


Figure 3.3 Gas centrifuge cascade [40].

3.5 Advantage of Gas Centrifuge

World is used two method for isotope separation. These methods are gas centrifuge and gas diffusion. Gas centrifuge is being currently used in 65 percent of the world for enrichment. Gas diffusion process is 35 percent of the world [20]. The reason in preference is less electricity consumption than the other enrichment techniques. The costs of enrichment are rate of electrical energy consumption. The electrical consumption of gas centrifuge plants consume about 60 kWh/SWU, while gaseous diffusion process requires only about 2400 kWh per SWU which is a the degree to which it is enriched [13]. The count of stages wanted to produce low-enriched uranium is about 30 times less in the gas centrifuge than in the gas diffusion. The corresponding equilibrium time is significantly shorter in centrifuge plants (hours) as compared to diffusion plants (months). The centrifuge plants are small in-process store and the elasticity to change the cascade design (parallel to series). Therefore, this plant is easy to close and change.

CHAPTER 4

Steady State Simple Gas Centrifuge Theory

4.1 Pressure Gradient of Pure Gases

Gas centrifuge is described as a rotor or closed cylinder rotates with high speed containing gas mixture or a pure gas. In the cylinder, pure gas rotates at same speed and it has no axial and radial motions. In the radial direction to prevent radial flow, pressure gradient is established to balance the centrifugal force $\left(\omega^2 \mathrm{r} / \mathrm{g_c}\right)$ that occurred by the rotation of the gas [41].

That is,

$$\frac{1}{\rho}\frac{\partial P}{\partial r}=\frac{\omega^2 r}{g_c} \tag{4.1}$$

where ρ =mass density,

P=Pressure and

g_c=Gravitational constant.

Assuming pure gas with molecular weight MW and using the ideal gas law, the equation of pressure gradient can be written as

$$\frac{1}{P}\frac{\partial P}{\partial r}=\frac{MW\omega^2 r}{RT} \tag{4.2}$$

which upon integration gives

$$\frac{P(r)}{P(0)}=\exp(\frac{MW\omega^2 r^2}{2RTg_c}) \tag{4.3}$$

where $P(0)$ is the pressure at the axis, r=0.

At the cylinder wall ($r=R_w$) the quantity ωR_w represented the inner wall peripheral speed of the cylinder, s (m/sec), i.e.,

$$P(wall)/P(axis) = \exp(\frac{MWs^2}{2RTg_c}) \tag{4.4}$$

Figure 4.1 and 4.2 illustrate values of the ratio, P (wall)/P (axis), attainable in a simple gas centrifuge operating at different peripheral speeds and containing pure gases of different molecular weight at 70 °F. As can be seen from the equation for P (wall)/P (axis), the limiting value of the ratio, as s or MW go to zero, is one. Hence, in order to distinguish small change from one Figure 4.1 contains a plot of P (wall)/P (axis)-1 due to the small molecular weights (2-100), whereas Figure 4.2 contains a plot of simply P (wall)/P (axis) with molecular weights between 100 and 400 [42].

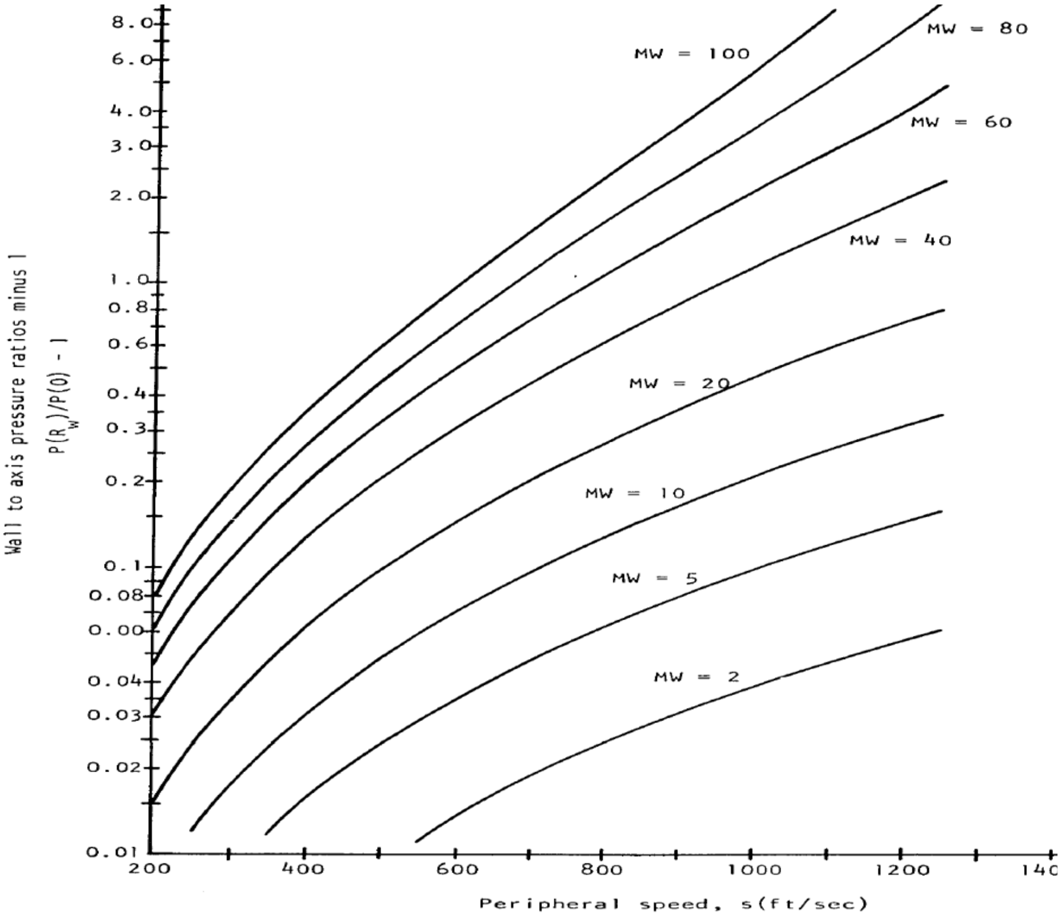


Figure 4.1 Wall to axis pressure ratios minus 1 versus peripheral speed various molecular weights between 2 and 100 [42].

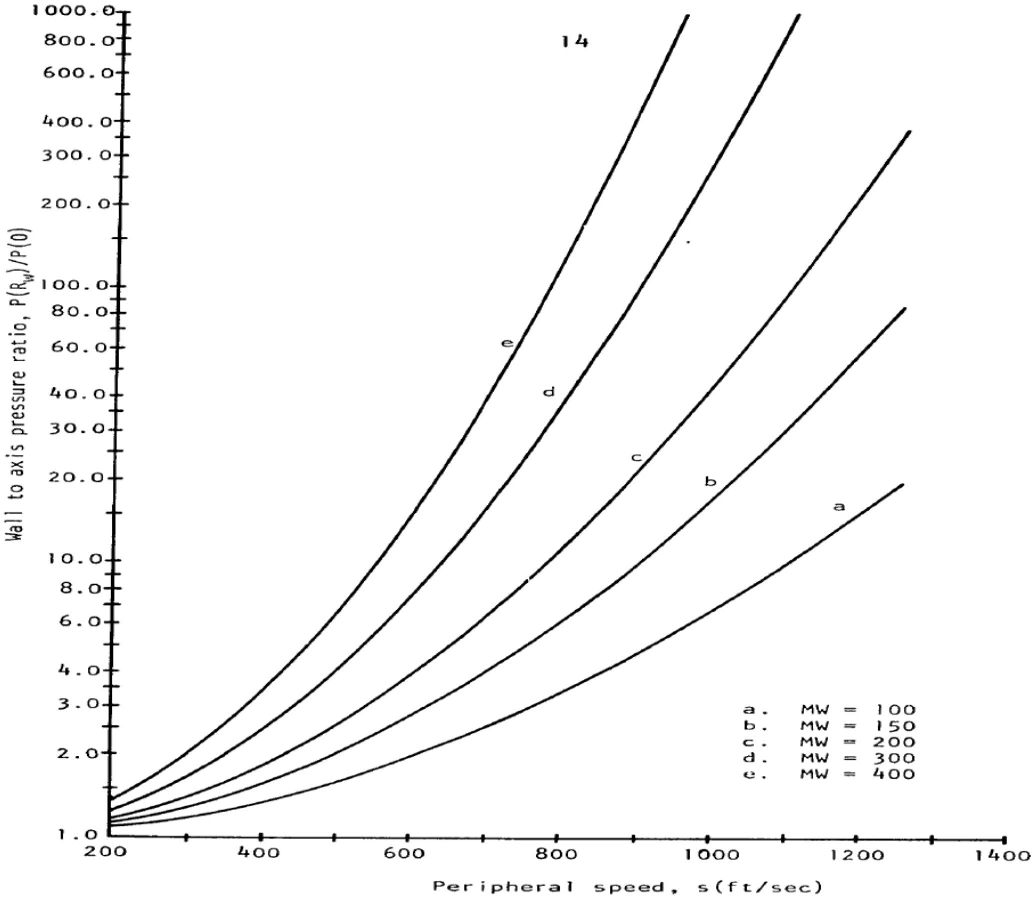


Figure 4.2 Wall to axis pressure ratios versus peripheral speed various molecular weights between 100 and 400 [42].

To illustrate the use of Figures 4.1 and consider sulfur dioxide (MW=64) in a simple gas centrifuge operating at 70 °F and a peripheral speed of 400 ft/sec. From Figure 4.1, P (wall)/P (axis)-1 is read as 0.36 (actual value=0.3547) [41].

Table 4.1. Data is used in steady state analysis of the gas pairs SO_2-N_2, SO_2-H_2 and UF_6 [41].

Parameter	SO_2-N_2	SO_2-H_2	UF_6(235,238 isotopes)
Charge pressure, atm	1	1	1
Charge density, y	0.002 (SO_2)	0.002 (SO_2)	0.007 (U_{235})
Centrifuge radius, cm	10	10	10
Centrifuge, rev/min	10000,20000	10000,20000	20000
Molecular weights	64-28	64-2	349-352
Temperature	20	20	27

Table 4.2 Data used to construct Figure 4.1.

Speed(s)	P(wall)/P(axis)-1						
	MW=2	MW=5	MW=10	MW=40	MW=60	MW=80	MW=100
200	0.0015191	0.0038020	0.0076186	0.0308245	0.0466591	0.006259	0.078852
300	0.0034212	0.0085750	0.0172236	0.0706948	0.107895	0.146387	0.186217
400	0.0060903	0.0152953	0.0308245	0.129117	0.199799	0.274905	0.354713
500	0.0095323	0.0240015	0.0485790	0.208940	0.329251	0.461535	0.606984
600	0.0137553	0.0347438	0.0706948	0.314204	0.506586	0.727131	0.979961
700	0.0187688	0.0475847	0.0974337	0.450485	0.746907	1.103910	1.533860
800	0.0245845	0.0625992	0.129117	0.625384	10.722	1.641870	2.368140
900	0.0312158	0.0798760	0.166132	0.849231	15.147	2.41965	3.650260
1000	0.0386780	0.0995180	0.208940	11.361	2.1220	3.562860	5.668780
1100	0.0469885	0.121643	0.258084	15.052	2.9651	5.275910	8.933360
1200	0.0561669	0.146387	0.314204	19.830	4.1520	7.898190	14.36830

Table 4.3 Data used to construct Figure 4.2.

Speed(s)	P(wall)/P(axis)			
	MW=100	MW=200	MW=300	MW=400
200	107.885	116.392	12.557	135.471
300	118.622	140.711	166.914	197.996
400	135.471	183.525	248.624	336.814
500	160.698	25.824	414.987	666.878
600	197.996	392.025	776.194	153.683
700	253.386	642.045	162.685	412.222
800	336.814	113.443	382.093	128.694
900	465.026	21.625	100.562	467.639
1000	666.878	444.726	296.578	1977.82
1100	993.336	986.717	980.142	9736.1
1200	153.683	236.186	3629.78	55783.8

4.2 Pressure Gradients of Gas Mixtures

If a perfect mixture of gas species is placed in a simple gas centrifuge a pressure gradient will be established for each species according to the equation developed in section 4.1. For example, for specie i we have

$$\frac{1}{P_i}\frac{\partial P_i}{\partial r} = \frac{MW_i \omega^2 r}{RTg_c} \tag{4.5}$$

And integrating as before gives

$$\frac{P_i(r)}{P_i(0)} = \exp(\frac{MW_i \omega^2 r^2}{2RTg_c}) \tag{4.6}$$

The total pressure at any point r is then defined by

$$P(r) = \sum_{i=1}^{n} P_i(0)\exp(\frac{MW_i \omega^2 r^2}{2RTg_c}) \tag{4.7}$$

Where n=number of species [41].

Due to the different molecular weights of each species, the individual partial pressures increase at different rates proceeding from the axis to the wall. Thus, the ratio of species i and j at the axis will differ from their ratios at any other position. This fact is illustrated by taking the ratios of the partial pressures of species i and j, i.e.,

$$\frac{P_i(r)}{P_j(r)} = \frac{P_i(0)}{P_j(0)}\exp\left[\frac{(MW_i - MW_j)\omega^2 r^2}{2RTg_c}\right] \tag{4.8}$$

Thus, if MW_i is greater than MW_j, the gas mixture near the wall will be more concentrated in the heavier (i^{th}) species [42].

With this observation in mind, all further analyses embodied in this wok will be restricted to binary gas mixtures. This is not to indicate that the concepts developed are restricted to only binary mixtures, but was done simply to simplify the equations and simplify the methods by which they may be analyzed.

4.3 Mole Fraction Distributions and Simple Separation Factors

In a binary gas mixture (species 1 and 2) the mole fraction (y) of the heavy species (taken as species 1) in a simple gas centrifuge can be written in terms of the partial pressures of the species, i.e.,

$$y(r)=\frac{P_1(0)\exp(\frac{MW_1\omega^2 r}{2RTg_c})}{P_1(0)\exp(\frac{MW_1\omega^2 r}{2RTg_c})+P_2(0)\exp(\frac{MW_2\omega^2 r}{2RTg_c})} \tag{4.9}$$

or

$$y(r)=\frac{1}{1+\frac{P_2(0)}{P_1(0)}\exp\left[\frac{(MW_2-MW_1)\omega^2 r^2}{2RTg_c}\right]} \tag{4.10}$$

If y(0) is the mole fraction at the axis, then using the pressure gradient equation given as [42]

$$P_2(0)=\left[1-y(0)\right]P(0), \tag{4.11}$$

$$P_1(0)=y(0)P(0) \tag{4.12}$$

Substitution of this information into the mole fraction equation and rearranging gives

$$y(r)=\frac{y(0)\exp(\frac{Ar^2}{2})}{y(0)\left[\exp(\frac{Ar^2}{2})-1\right]+1} \tag{4.13}$$

where

$$A=\frac{(MW_1-MW_2)\omega^2}{RTg_c}=\frac{\Delta MW\omega^2}{RTg_c} \tag{4.14}$$

Although equation is time independent, we increased centrifugal speed (ω) to see interval steps. Therefore, graphical user interface is drawn graphs of mole fraction as time dependent.

The equation used to compute y(0) was

$$y(0)=\frac{y_f\,\frac{q_1}{q_2}C}{1+y_f\,(\frac{q_1}{q_2}C-1)} \qquad (4.15)$$

where
$$C=\frac{\exp(q_2R_w^2/2)-1}{\exp(q_1R_w^2/2)-1} \qquad (4.16)$$

$$q_1=\frac{MW_1\omega^2}{RTg_c} \quad \text{and} \quad q_2=\frac{MW_2\omega^2}{RTg_c} \qquad (4.17)$$

This expression allows one to compute the mole fraction profile in a simple gas centrifuge given A and y (0).

The profiles were the computed by following equation:

$$y(R_w)=\frac{y(0)\exp(\frac{Ar^2}{2})}{y(0)\left[\exp(\frac{Ar^2}{2})-1\right]+1} \qquad (4.18)$$

where

$$A=\frac{MW\omega^2}{RTg_c}\,. \qquad (4.19)$$

The calculated data used to construct Figure 4.3 are found in Table 4.4.

A separation factor for the simple gas centrifuge may be defined as the ratio of species 1 to 2 at the wall to the ratio of species 1 to 2 at the axis, i.e.,

$$\alpha=\frac{y(R_w)}{1-y(R_w)}.\frac{1-y(0)}{y(0)} \qquad (4.15)$$

or, in terms of the mole fraction distribution given above,

$$\alpha = \frac{1-y(0)}{y(0)} \frac{y(0)\exp(\frac{AR_w^{\ 2}}{2})}{y(0)\left[\exp(\frac{AR_w^{\ 2}}{2})-1\right]+1-y(0)\exp(\frac{AR_w^{\ 2}}{2})} \tag{4.16}$$

Which simplifies to

$$\alpha = \exp(\frac{AR_w^{\ 2}}{2}) \tag{4.17}$$

An expression for y (R_w) can now be written in terms of α, i.e.,

$$y(R_w) = \frac{\alpha y(0)}{y(0)(\alpha-1)+1} \tag{4.18}$$

Since the expression for α is identical to that developed for the ratio P (wall)/P (axis) for a pure gas, expect that molecular weight difference appears in the exponential instead of an actual molecular weight. Figures 4.1 and 4.2 can be used to estimate values of α by just substituting molecular weight difference. For example, consider a mixture of hydrogen (MW=2) and sulfur dioxide (MW=64) at 70 °F in a simple centrifuge with a peripheral speed of 500 ft/sec. From Figure 4.1 with MW=62, α-1 is found to be 0.34 (actual value=0.3419) and then using Figure 4.1 giving α-1=0.22 (actual value=0.2198) [42].

Table 4.4 Data used to construct Figure 4.3.

Dimensionless Radius (r/R_w)	SO_2-N_2	SO_2-H_2	UF_6
	y, SO_2	y, SO_2	y,U_{235}
0.0	0.001830	0.001720	0.0020180
0.1	0.001833	0.001725	0.0020178
0.2	0.001843	0.001740	0.0020169
0.3	0.001858	0.001776	0.0020155
0.4	0.001881	0.001802	0.0020135
0.5	0.001909	0.001851	0.0020109
0.6	0.001946	0.001912	0.0020078
0.7	0.001989	0.001986	0.0020041
0.8	0.002041	0.002076	0.0019998
0.9	0.002101	0.002182	0.0019950
1.0	0.002170	0.002307	0.0019896

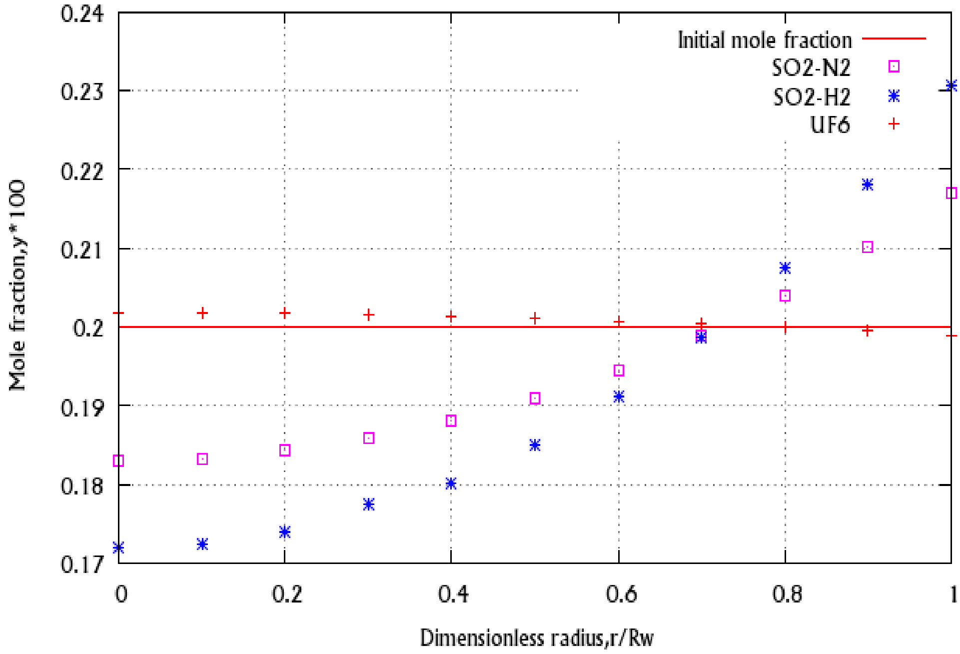


Figure 4.3 Mole fraction in a gas centrifuge at 20 °C for the gas pairs.

An important aspect to be noted in the expression for α is that it is a function of molecular weight difference, not the ratio of the molecular weights or the molecular weight difference divided by the sum of molecular weights as in diffusion processes. This gives the gas centrifuge an important advantage for separating heavy gases, hence the interest in the field of gas centrifugation for the separation of Uranium isotopes (5, 6, 7, and 8) (ΔMW=3) when gasified as uranium hexafluoride (MW=352) [41].

All calculated data and graphs are transferred graphical user interface (GUI) and shown display screen. Graphical user interface is explained in Chapter 5. We used programming language C++ and added all program in Appendix. The coded program is both records the output data into a file, plots and visualize the separation of the isotopes on the computer display screen by using the steady state analysis. One could use it to obtain data and graph by entering only the molecular weight of desired gasses.

Graphical user interface is given in Figure 5.1 in next chapter.

CHAPTER 5

GRAPHICAL USER INTERFACE

5.1 Introduction of GUI

Graphical user interface is the general name for humans to interact with computers that use icons, windows, buttons and panels which can be changed by mouse. Other user interface is command-line interface (CLI). The user enters commands by typing the acts in this interface such as DOS. It use only text and reached solely by a keyboard. DOS contain some features of GUIs but they are not graphical. Another CLI is Linux that it is used console mode. The entire screen shows text only in Linux.

The graphical user interface was firstly devised by Xerox Corporation's Palo Alto Research Center in the 1970s, but it became popular with emergence of the Apple Macintosh in 1980s. Because they are necessary notable central processing unit (CPU) power and a high-quality monitor for graphical user interface (GUI).

In this study, a GUI have been designed and coded together with the simulation by the programming language C + +. Because GUI make easier to decipher produced as the output. A plot of concentrations and the centrifuge process visualized by different colors for each separated isotope have also presented as the screen output.

5.2 Basic Component

There are many features of basic component of GUI such as pointer, pointing device, icons, desktop and menus. Pointer is a symbol that looks as a small angled arrow on the screen and we carry out to select commands and objects. Pointing device supplies us to select objects on the display screen such as a mouse. Icons are small pictures that used to see or operate windows, files, or commands. We can convert the icon or execute a command into a window. Desktop is a collection of all the icons and the buttons on the display screen. GUI and Windows are split the screen into different sections. In divided windows, one can write a different program or execute program independently from other windows and GUI’s. A main feature of the windows is the capability to be open for multiple windows. Menus carry out required C++ commands changing with a choice from a menu presented at GUI.

There are also many some other components used in GUI. For this study, other details of the designed and coded GUI will not be explained in detailed since they are barely the programming.

5.3 Simulation

Simulation imitate event of the real world system or process. Simulation of a system is the process of creating a model that could represent this system. The purpose of simulation experiments to understand the behavior of the system or evaluate different strategies for the design and operation of the system. If the simulation is run on a computer, it is called a computer simulation. Computer simulation can be studied to see how the system works if analytic methods are unavailable. Predictions may be made about the behavior of the system by changing some variables in the simulation. It is a tool to virtually investigate the behavior of the system under study [43]. Computer simulation and visualization have become a useful part of modeling many natural systems in physics, chemistry and biology and human systems in economics and social science (the computational sociology) as well as in engineering to gain insight into the operation of those systems. In each simulation, the presented visual represented of data will change each cycle or phase due to the set of initial parameters assumed for the model during the execution. Simulation and visualization are extensively used for educational purposes and the training of civilian and military personal.

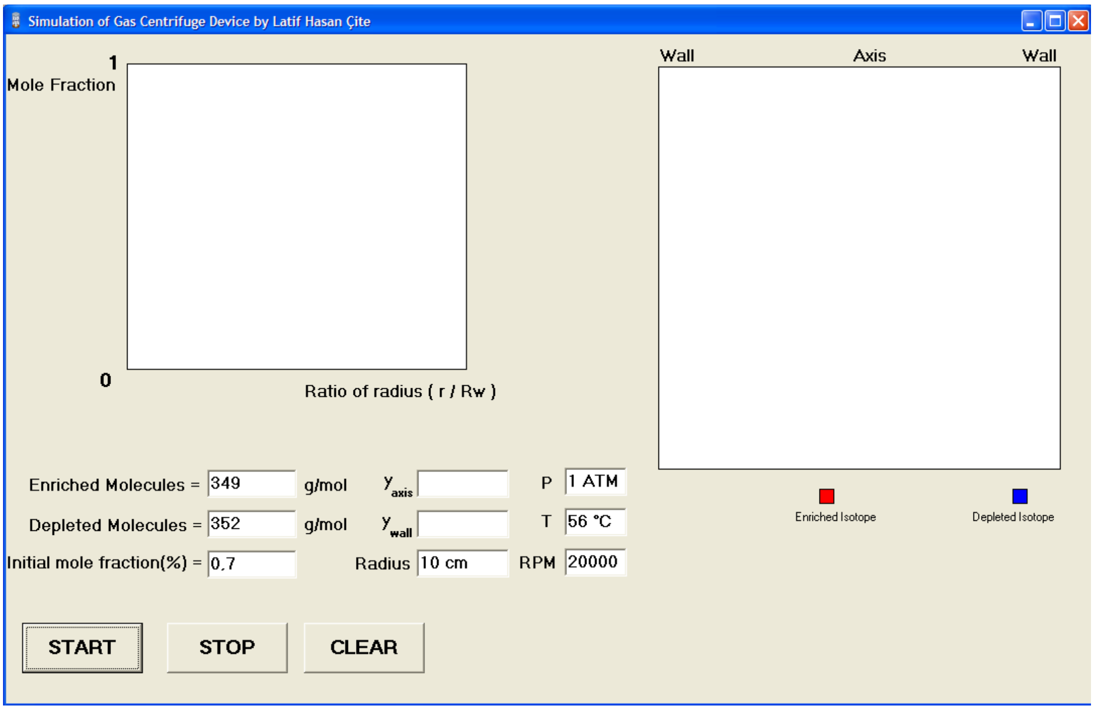
There are more simulation examples in various areas. For example,

- Engineering, technology or process simulators
- Economics simulators
- Automobile simulator
- Biomechanics simulators
- Communication satellite simulators
- Flight simulators
- Space shuttle countdown simulators

5.4 GUI and usage

We assume the initial value for variables that pressure, temperature, RPM (radius per minute), centrifuge radius are 1 atm, 50°C, 20000, 0.1 m respectively. Other variables that can be controlled manually are enriched molecule weight (desired molecules for enrichment), depleted molecule weight (wasted molecules) and initial mole fraction for enriched molecules. y_{center} is the mole fraction for enriched molecules in centrifuge center and y_{wall} is the mole fraction for depleted molecules in centrifuge wall.

Start button starts the simulation program and plots graph and outputs the animated simulation of the isotopes separation using the results of the solution for the steady state analysis. The listing of the program presented in the Appendix.



Simulation of Gas Centrifuge Device by Latif Hasan Çite

Enriched Molecules = 349 g/mol

Depleted Molecules = 352 g/mol

Initial mole fraction(%) = 0,7

y_{axis}

y_{wall}

Radius 10 cm

P 1 ATM

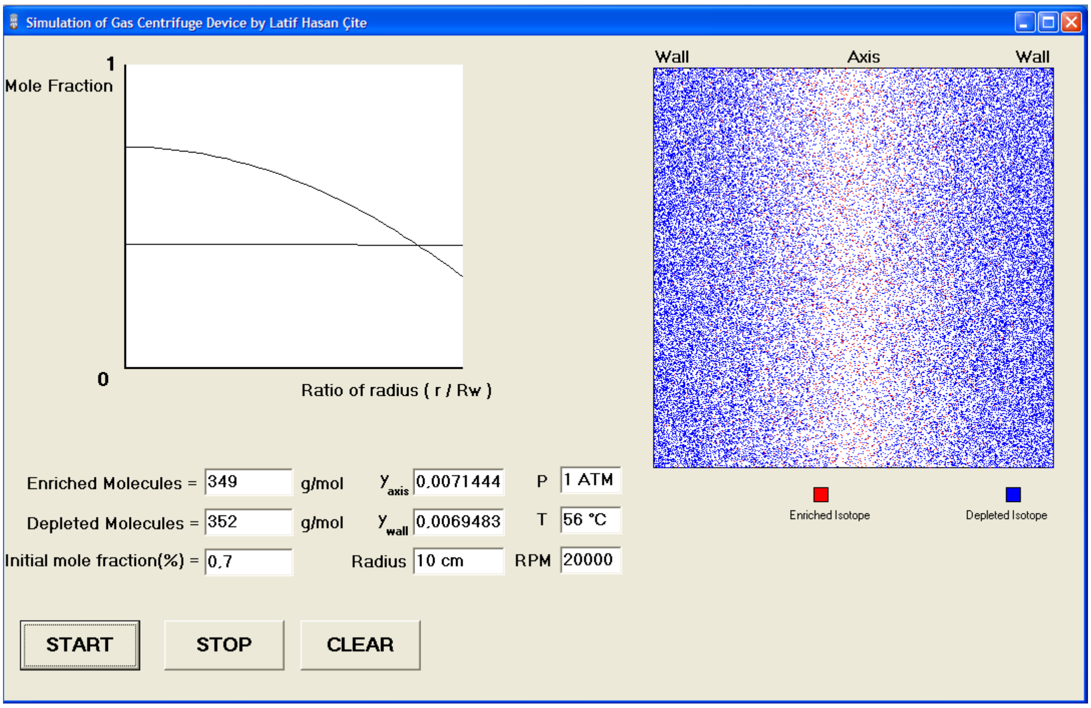
T 56 °C

RPM 20000

Figure 5.1 Prepared graphical user interface initially.

Mole fraction for enriched molecules versus ratio of radius graph is depicted in the left side of the screen. X axis of the graph represents the radius of centrifuge from center to wall. Also right side of the screen displays the simulation and animation of the enrichment molecules by gas centrifuge method. Red point and blue point represent enriched molecules and wasted molecules in turn.

The user interface of the simulation program for the input initial conditions of the execution and the last screen after the all resulting data have been plotted and visualized are shown below as Figure 5.1 and Figure 5.2.



Enriched Molecules = 349 g/mol

Depleted Molecules = 352 g/mol

Initial mole fraction(%) = 0.7

y_{axis} 0.0071444

y_{wall} 0.0069483

Radius 10 cm

P 1 ATM

T 56 °C

RPM 20000

Figure 5.2 Prepared graphical user interface finally.

5.5 Comparison of the Results

Since the field of the present work is a field which has strict rules, nuclear and military not more than one study have been found. As shown in graph the output data of the simulation for UF_6, SO_2 - N_2 and SO_2-H_2 is nearly coherent and logical with only available Auvil's work [42]. The other gas mixtures or pure gases can be simulated for the separation by the method with the present work. For example, CO_2-H_2S (removal CO_2 from natural gas) can be seen in Figure 5.6 below. This program enables one easily to demonstrate the separation of the gases without solving the steady state mole fraction equation 4.13.

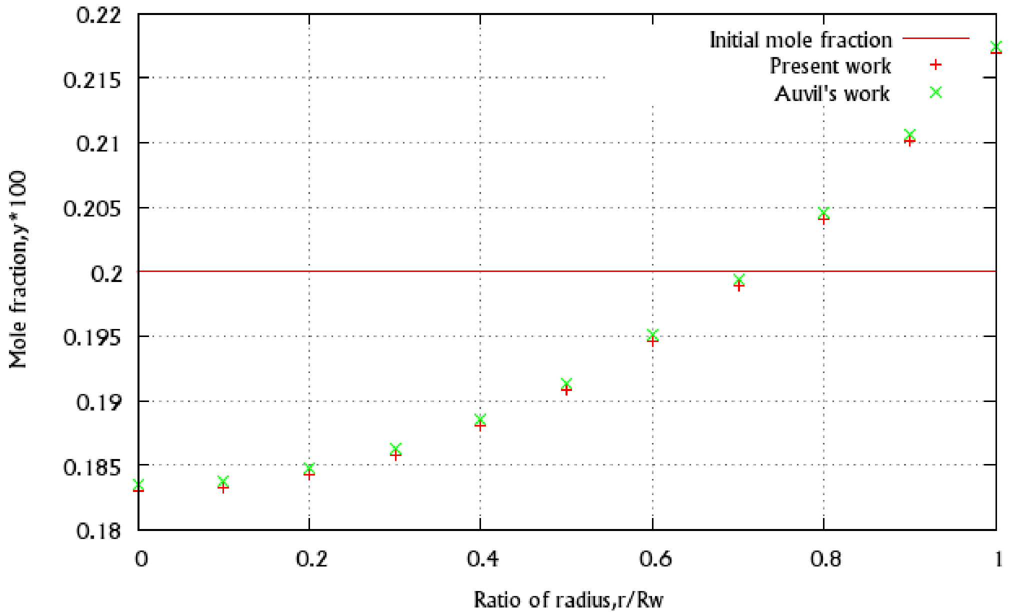


Figure 5.3 Comparison of present work and Auvil’s work for SO_2-N_2 gas mixture.

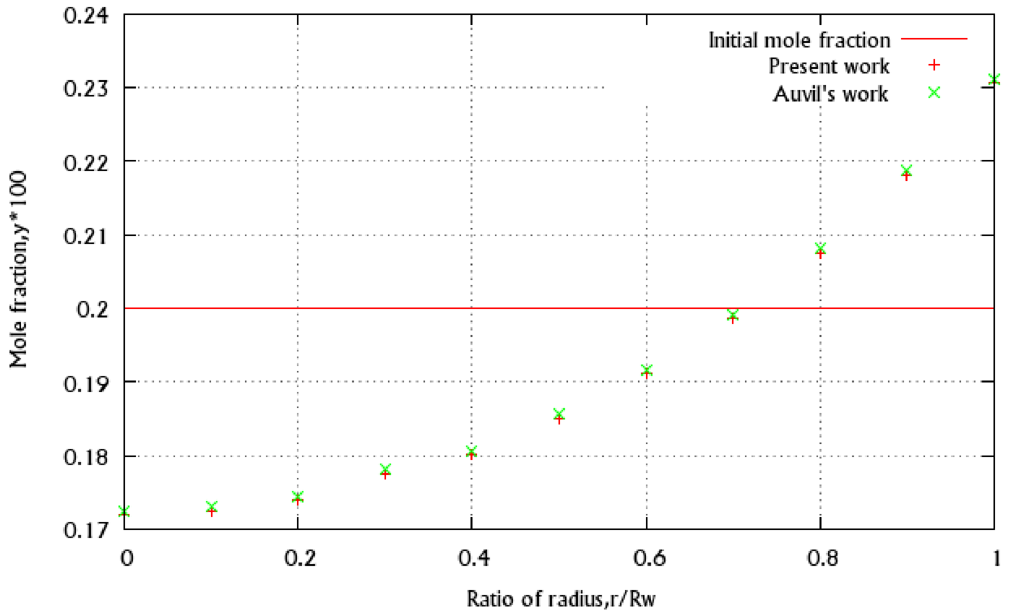


Figure 5.4 Comparison of present work and Auvil’s work for SO_2-H_2 gas mixture.

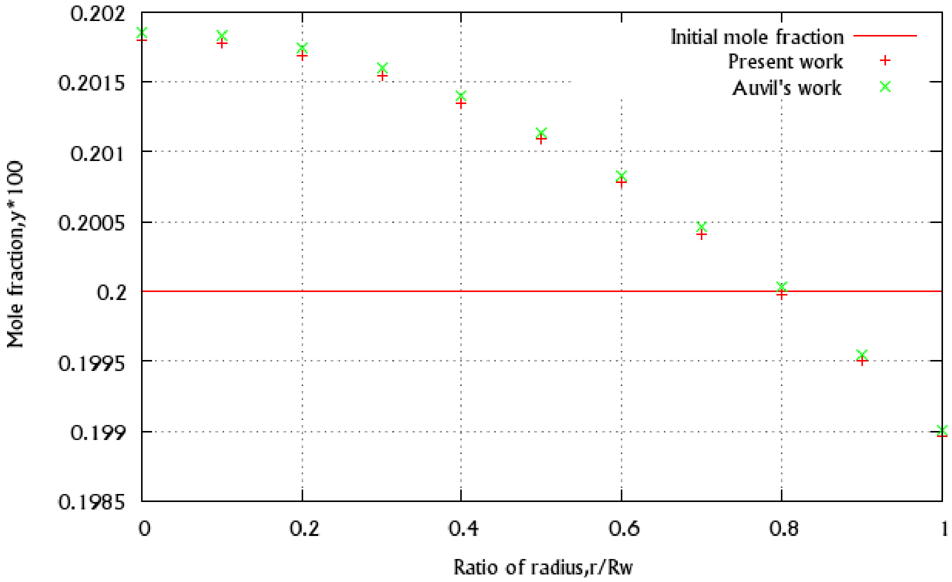


Figure 5.5 Comparison of present work and Auvil’s work for UF_6 molecules.

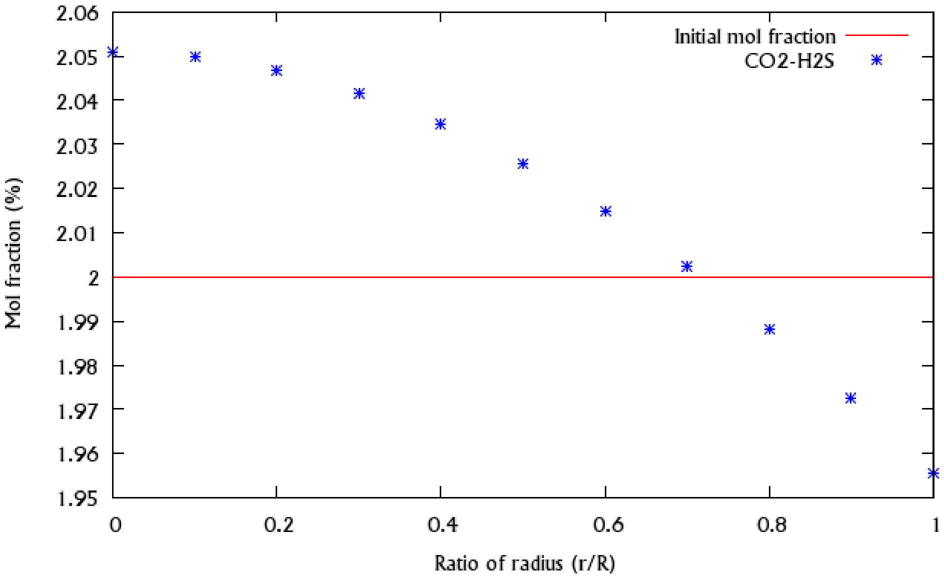


Figure 5.6 Plot of mole fraction for CO_2-H_2S.

CONCLUSION

Nuclear power has been favored because it enhances energy security and due to shortages or insufficiencies of renewable energy as an alternative source of energy while allowing electric utilities to meet stated environmental objectives. Uranium has an important factor at fuel enrichment and amount of little uranium raw materials generate high electricity. Gas centrifuges are the popular method at worldwide for the nuclear fuel enrichment industry. Gas centrifuge is being currently used in 65% of the world for enrichment. In the following few years it is estimated that its usage will be reach over 93%. The main factor is less electricity consumption than other enrichment techniques.

In this study, an observation for separation of some gases; i.e; SO_2-N_2, SO_2-H_2 and UF_6 gases with gas centrifuge method were investigated. Mole fraction of gases were calculated and visualized by gas centrifuge method. Plot of mole fraction together with visual representation of the separation of gas in gas centrifuge device was presented and compared with available data. The result of the present work is almost consistent with the one presented at available study of Auvil's [42].

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APPENDIX

Program listing including Graphical User Interface (GUI) of the simulation and animation is given below.

```
//---------------------------------------------------------------------------
#include <vcl.h>
#pragma hdrstop
#include "Unit1.h"
#include "math.h"
//---------------------------------------------------------------------------
#pragma package(smart_init)
#pragma link "CSPIN"
#pragma resource "*.dfm"
TForm1 *Form1;
//---------------------------------------------------------------------------
__fastcall TForm1::TForm1(TComponent* Owner)
        : TForm(Owner)
{
MoveWindowOrg(Form1->Image1->Canvas->Handle, 0, 304);
Form1->Image1->Canvas->MoveTo(0,-152);
Form1->Image1->Canvas->Rectangle(0,0,Image1->ClientWidth,-1*Image1->ClientHeight);
Form1->Image2->Canvas->Rectangle(0,0,Image2->ClientWidth,Image2->ClientHeight);
```

```
//Form1->Image1->Canvas->FillRect(ClientRect);
//Form1->Image2->Canvas->FillRect(ClientRect);
}
//---------------------------------------------------------------------------
void ciz(double x, double y, double kats, double minp){
x=Form1->Image1->ClientWidth*x;
y=-1*Form1->Image1->ClientHeight*kats*(y-minp)+minp;
Form1->Image1->Canvas->LineTo(x,y);
}
//---------------------------------------------------------------------------
void maxmin(double w2){
  const int n = 40;
  double xx1[n],yy1[n];
  double Q1, Q2, M1, M2, w, RT, g, R, A, y0, y, r, yf, C;
  double yy, dr, dw, wmax;
  w=w2;

   M1= StrToFloat(Form1->Edit1->Text)*1.0e-3;
   M2= StrToFloat(Form1->Edit2->Text)*1.0e-3;

  RT  = 8.3144621*293/9.8;
  g   = 9.8;    // m/s2
  R   = 0.1016; // m

  yf = StrToFloat(Form1->Edit3->Text)*1.0e-2;
  dr  = R/n;
    A  = (M1-M2)*w*w/(RT*g);
```

```
   Q1 = M1*w*w/(RT*g);
   Q2 = M2*w*w/(RT*g);
   r = 0;
   double sum1=0,sum2=0;
    for(int i=0; i<=n; i++){
          y  = y0*exp(A*r*r/2) /(y0*(exp(A*r*r/2)-1)+1);
      yy = y;
      if(i<20)sum1 = sum1 + yy;
      if(i>=20)sum2 = sum2 + yy;
     if(i==0) Form1->Edit4->Text = FloatToStr(yy);
     if(i==40) Form1->Edit5->Text = FloatToStr(yy);
           r = r + dr;
                          }
}
////////////////////////////////////////////////////////
void grafik(double w2){
const int n = 40;
  double Q1, Q2, M1, M2, w, RT, g, R, A, y0, y, r, yf, C;
  double xx, yy, dr, dw, wmax;
  w=w2;


   M1= StrToFloat(Form1->Edit1->Text)*1.0e-3;
   M2= StrToFloat(Form1->Edit2->Text)*1.0e-3;
   RT  = 8.3144621*293/9.8;
    g   = 9.8;    // m/s2
   R   = 0.1016; // m
   yf  = StrToFloat(Form1->Edit3->Text)*1.0e-2;
```

```
  dr  = R/n;
     A  = (M1-M2)*w*w/(RT*g);
    Q1 = M1*w*w/(RT*g);
    Q2 = M2*w*w/(RT*g);
  r = 0;
    double minorsayi[41];
     for(int i=0; i<=n; i++){
      y  = y0*exp(A*r*r/2) /(y0*(exp(A*r*r/2)-1)+1);
       xx = r/R;
       yy = y;

      double maxpoint,minpoint,katsayi;
       minpoint = StrToFloat(Form1->Edit4->Text) - yf/20.0;
       maxpoint = StrToFloat(Form1->Edit5->Text) + yf/20.0;
       katsayi = 1.0/(maxpoint - minpoint);
       ciz(xx,yy,katsayi,minpoint);

       minorsayi[i]=yy;
       r = r + dr;

                            }
}
//---------------------------------------------------------------------------
void __fastcall TForm1::Button1Click(TObject *Sender)
{
maxmin(2100);
for(int i=0;i<20;i++){
```

```
ListBox1->Items->Add(140*1.5);
ListBox2->Items->Add(1860*1.5);
                }
Timer1->Enabled=true;
Timer2->Enabled=true;
}
//---------------------------------------------------------------------------
void __fastcall TForm1::Timer1Timer(TObject *Sender)
{
MoveWindowOrg(Form1->Image1->Canvas->Handle, 0, 303);
Form1->Image1->Canvas->Rectangle(1,0,ClientWidth,-1*ClientHeight);
Form1->Image1->Canvas->Pen->Color=clBlack;

Form1->Image1->Canvas->MoveTo(0,-152);
grafik(100);
Form1->Image1->Canvas->MoveTo(0,-152);
we->Value=we->Value + 100;
grafik(we->Value);

if(we->Value>2100){we->Value=100;Timer1->Enabled=false;Timer2->Enabled=false;}


}
//---------------------------------------------------------------------------
void __fastcall TForm1::Timer2Timer(TObject *Sender)
{
Form1->Image2->Canvas->Rectangle(0,0,Image2->ClientWidth,Image2->ClientHeight);
```

```
int xpoint,ypoint,xpointb,ypointb;

 for(int i=0;i<ListBox1->Items->Count;i++){

 for(int j=0;j<StrToInt(ListBox1->Items->Strings[i]);j++){

          xpoint = rand()%20 + i*20;

          ypoint = rand()%450;

          Form1->Image2->Canvas->Pixels[xpoint][ypoint]=clRed;

          Form1->Image2->Canvas->Pixels[-1*xpoint][ypoint]=clRed;

                                                 }

 }

for(int i=0;i<ListBox2->Items->Count;i++){

 for(int j=0;j<StrToInt(ListBox2->Items->Strings[i]);j++){

          xpointb = rand()%20 + i*20;

          ypointb = rand()%450;

          Form1->Image2->Canvas->Pixels[xpointb][ypointb]=clBlue;

          Form1->Image2->Canvas->Pixels[-1*xpointb][ypointb]=clBlue;

                                                 }

}

  for(int i=0;i<5;i++){

   ListBox1->Items->Strings[i] = StrToInt(ListBox1->Items->Strings[i]) + (i*2-10);

   ListBox2->Items->Strings[i] = StrToInt(ListBox2->Items->Strings[i]) - 10*(i*2-
10);

                       }

for(int i=5;i<10;i++){

   ListBox1->Items->Strings[i] = StrToInt(ListBox1->Items->Strings[i]) + (i*2-8);

   ListBox2->Items->Strings[i] = StrToInt(ListBox2->Items->Strings[i]) - 10*(i*2-
8);

                        }

for(int i=10;i<15;i++){
```

```
        ListBox1->Items->Strings[i] = StrToInt(ListBox1->Items->Strings[i]) + (30-
i*2);
        ListBox2->Items->Strings[i] = StrToInt(ListBox2->Items->Strings[i]) - 10*(30-
i*2);
}
for(int i=15;i<20;i++){
       ListBox1->Items->Strings[i] = StrToInt(ListBox1->Items->Strings[i]) + (28-
i*2);
       ListBox2->Items->Strings[i] = StrToInt(ListBox2->Items->Strings[i]) +
10*(i*2-28);
                         }
}
//---------------------------------------------------------------------------
void __fastcall TForm1::Button2Click(TObject *Sender)
{
Timer1->Enabled=false;
Timer2->Enabled=false;
}
//---------------------------------------------------------------------------
void __fastcall TForm1::Button3Click(TObject *Sender)
{
Timer1->Enabled=false;
Timer2->Enabled=false;
we->Value=100;
ListBox1->Items->Clear();
ListBox2->Items->Clear();
Image1->Canvas->FillRect(ClientRect);
Image2->Canvas->FillRect(ClientRect);
```

```
Form1->Image1->Canvas->Rectangle(0,0,Image1->ClientWidth,Image1->ClientHeight);

Form1->Image2->Canvas->Rectangle(0,0,Image2->ClientWidth,Image2->ClientHeight);

}

//---------------------------------------------------------------------------
```