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DESIGN AND ANALYSIS OF A GREENER DISPOSAL SYSTEM FOR ENERGETIC MATERIALS AND MUNITIONS

M.Sc. Thesis by

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DESIGN AND ANALYSIS OF A GREENER DISPOSAL SYSTEM FOR ENERGETIC MATERIALS AND MUNITIONS

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M.Sc. THESIS EXAMINATION RESULT FORM

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DESIGN AND ANALYSIS OF A GREENER DISPOSAL SYSTEM FOR ENERGETIC MATERIALS AND MUNITIONS

ABSTRACT

Demilitarization is becoming more and more significant in management of the munitions since all munitions have a finite lifetime and these munitions can reach their service life for a variety of reasons such as; the process of natural aging, becoming obsolete due to the development of new systems, becoming surplus because of the changed requirements or requirement to be destroyed owing to international agreements. Military munitions, pyrotechnics, and vehicle airbag propellants are examples of energetic materials, which contain a large quantity of stored chemical energy that can be released. In this study, it has been aimed to review available demilitarization process, asses their environmental impact and identify their advantages and disadvantages. The study is primarily focus on disassembly, removal of energetics and destruction phases. Computational Fluid Dynamics (CFD) analyses has been carried out for the multiphase flow of the water-explosive slurry and flow behavior in different configurations has been investigated. Results of the analysis are discussed considering sensitivity of energetic material in these configurations.

Keywords: System Design, Energetic Materials, Munitions, Greener Disposal, Demilitarization, CFD

ENERJİK MALZEME VE MÜHİMMATLAR İÇİN DAHA ÇEVRECİ BİR BERTARAF SİSTEMİ TASARIMI VE ANALİZİ

ÖZET

Tüm mühimmatların sınırlı bir kullanım ömrüne sahip olması ve bu mühimmatların doğal yaşlanma süreci, yeni sistemlerin gelişmesi nedeniyle modası geçmiş olması, değişen gereksinimler nedeniyle fazlalık haline gelmesi veya uluslararası anlaşmalar nedeniyle yok edilmesi gerekliliği gibi çeşitli sebeplerle hizmet ömürlerine ulaşabilmesi nedeniyle, mühimmat yönetiminde demilitarizasyon giderek daha fazla önem kazanmaktadır. Askeri mühimmat, piroteknik ve araç hava yastığı itici gazları, salınabilecek büyük miktarda depolanmış kimyasal enerji içeren enerjik malzemelere örnektir. Bu çalışmada, mevcut demilitarizasyon sürecinin gözden geçirilmesi, çevresel etkilerinin değerlendirilmesi, avantaj ve dezavantajlarının belirlenmesi amaçlanmıştır. Çalışma öncelikle demontaj, enerjik malzemelerin çıkarılması ve imha aşamalarına odaklanmaktadır. Su ve patlayıcı karışımının çok fazlı akışı için Hesaplamalı Akışkanlar Dinamiği (HAD) analizleri yapılmış ve farklı konfigürasyonlardaki akış davranışı incelenmiştir. Analiz sonuçları, bu konfigürasyonlarda enerjik malzemenin duyarlılığı dikkate alınarak tartışılmıştır.

Anahtar Kelimeler: Sistem Tasarımı, Enerjik Malzeme, Mühimmat, Çevreci Bertaraf, Demilitarizasyon, CFD

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NOMENCLATURE

Roman Letter Symbols

Cp	Specific heat, J/kg·K
E_r	Mechanical energy per unit mass, J/kg
F	Volume force, N/m^3
g	Gravitational acceleration, m/s^2
h_r	Sensible enthalpy for phase r, J/kg
k	Turbulence kinetic energy, m^2/s^2
k_{eff}	Effective conductivity, W/m·K
m_{max}	Mass of the maximum sized element, kg
p	Static pressure, Pa
P_m	Mixture outlet pressure, Pa
P_{rt}	Pressure ratio
P_s	Secondary inlet pressure, Pa
S_E	Any other volumetric heat source, J
t	Time, s
T	Temperature, K
T_m	Mixture temperature outlet, K
T_p	Primary fluid inlet temperature, K
u_m	Mixture velocity, m/s
u_r	Velocity vector of phase r, m/s
V_{max}	Maximum element volume, m^3

Greek Letter Symbols

α_r	Volume fraction of phase r
ε	Turbulence dissipation rate, m^2/s^3
∇p	Pressure gradient, Pa/m
μ	Viscosity, cP
μ_m	Viscosity coefficient of the mixture, Pa·s
μ_t	Turbulence viscosity, Pa·s
ρ_m	Mixture density, kg/m^3

ρ_r	Density of phase r, kg/m^3
ρ_{TNT}	Density of TNT, kg/m^3
τ_{ij}	Turbulence stress tensor, Pa
θ	Heating coefficient

Subscripts

E	Any other
eff	Effective
ij	x-y plane on coordinate system
m	Mixture
max	Maximum
p	Turbulent
r	Phase r
rt	Ratio
s	Secondary
t	Turbulent
TNT	TNT material

Acronyms

1D	One-dimensional
AFJ	Abrasive Fluid Jet
ASJ	Abrasive Slurry Jet
AWJ	Abrasive Water Jet
CFD	Computational Fluid Dynamics
CO_2	Carbon Dioxide
Comp-B	Composition B
EU	European Union
HCl	Hydrogen Chloride
HCN	Hydrogen Cyanide
HMX	High-velocity Military Explosive
NATO	North Atlantic Treaty Organization
NC	Nitrocellulose

NEQ	Net Explosive Quantity
NG	Nitroglycerin
NOx	Nitrogen Oxides
OB	Open Burn
OD	Open Detonation
PBX	Polymer-bonded Explosive
PIV	Particle Image Velocimetry
RDX	Royal Demolition Explosive
SOx	Sulfur Oxides
STANAG	Standardization Agreement
TNT	Trinitrotoluene
UXO	Unexploded Ordnance
VOC	Volatile Organic Compound

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CHAPTER 1

INTRODUCTION

Several countries are dealing with a surplus of munitions, some of which were even left over from World War I. Since all munitions have a finite lifetime, these munitions can reach their service life for a variety of reasons such as; the process of natural aging, becoming obsolete due to the development of new systems, becoming surplus because of the changed requirements or requirement to be destroyed owing to international agreements. Thus, demilitarization is becoming more and more significant in management of the munitions. The stockpile of demilitarization munitions in Western nations is estimated to be in excess of half a million tons [1].

The NATO Standardization Agency has published STANAG 4518, which suggests that any NATO participating country developing a munition shall implement the design and assessment principles of demilitarization [2]. NATO STANAG 4518 [2] defines demilitarization as: “The act of removing or otherwise nullifying the military potential of a munition. Such action is to be carried out in a safe, cost-effective, practicable and environmentally responsible manner. Demilitarization is a necessary step for military items prior to their release to a non-military setting”. Despite the fact that the act of demilitarization always requires elimination/recycling of the energetic material, it does not necessary to destruct the components of the munition. Military munitions, pyrotechnics, and vehicle airbag propellants are examples of energetic materials, which contain a large quantity of stored chemical energy that can be released [3].

In order to destruct an energetic material, thermal and chemical disposal techniques can be applied. Thermal disposal techniques always comprehend a detonation such can be occur in kiln/chamber or a combustion process that can be happen in open air. For the chemical disposal techniques, processes such as oxidation or biodegradation take place.

Disposal of the surplus munitions by open burning/open detonation (OB/OD) is the most widespread and well known demilitarization process even though it has been

known that such solution has significant impact on the environment. Comparison of emission values for different methods in terms of gram equivalent concentration of air pollutants having equal toxic impact as the same concentration of NO_2 (NEQ) per kilogram mass of energetic material is given in Table 1.1. The main reason for the widespread use of OB/OD is that OB/OD is the cheapest disposal method. Despite the studies to qualify the unavoidably uncontrollable emissions of OB/OD, generation of dangerous pollutants such as dioxins and furans cannot be eliminated due to the low temperatures and non-uniform combustion. Additionally, properties can be damaged due to the shock waves produced by the open detonation and people can be harmed or killed by the projection of the debris. From an environmental perspective, it will be more convenient to prevent OB/OD other than the cases where reaching to the munition without any danger cannot be ensured. A practical example is Unexploded ordnance (UXO) whose any handling, manipulation or transportation poses a high degree of risk.

Table 1.1 Emission of Methods in terms of NO_2 equivalent [4]

Method	**Process Emissions (gram NEQ per kilogram mass of energetic material)**
Open Burning	285
Open Detonation	141
Closed Detonation	14
Fluidized Bed Oven	70
Rotary Kiln	75

From a general point of view, demilitarization process involves the order of operations given below despite the fact that not all of the steps listed are essential [1];

- Transportation
- Unpacking
- Disassembly
- Removal of Energetics
- Destruction
- Resource Recovery and Recycling

In this study, it has been aimed to review available demilitarization process and asses their environmental impact. The study will primarily focus on disassembly, removal of energetics and destruction phases. Considering transportation and unpacking are outside of the scope of this study, they will not be examined. Moreover, dumping and landfill/burial are also omitted since these type of disposal is prohibited by law in most countries.

After the review section, a particular analysis will be presented for a specified problem of hot water washout system and results will be discussed in the next section. In this analysis, multiphase flow of the water-explosive slurry will be investigated for different configurations. Finally, study will be concluded by summarizing main arguments and findings and present the ideas about the possible future works.

CHAPTER 2

REVIEW OF DISPOSAL TECHNIQUES

In this section, several munition demilitarization and disposal techniques will be reviewed. These techniques basically entail the dismantling of the munition so that various components could be detached. Selection of the applicable technique is subjected to several parameters such as the condition and location of the munition. For all of the techniques described below, safety, environmentally friendly and cost effective measures should be primarily focused.

2.1 Disassembly

The main objective of the disassembly is to reveal energetic material inside the munition so that a removal technique can be applied later. In order to reach the energetic material, a combination of reverse engineering, punching, pressing or cutting with a saw is used in aforementioned techniques.

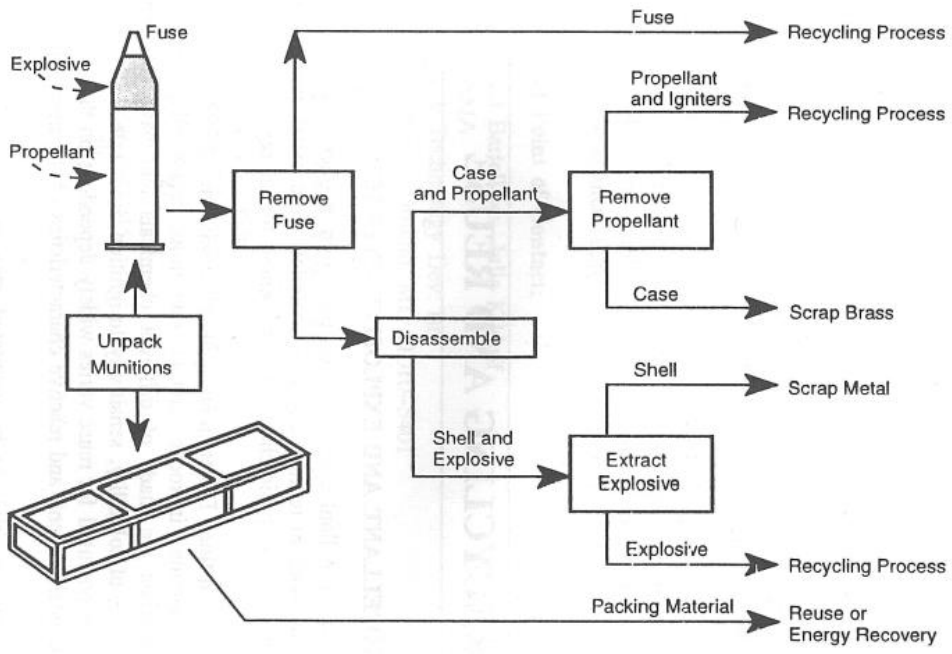

Figure 2.1 Flowchart for the Disassembly Process [5]

2.1.1 Reverse Assembly

In reverse assembly, munition components were dismantled by means of mechanical systems hind-foremost of manufacturing assembly order. Although the process of reverse assembly can be carried out manually, necessity of highly qualified personnel and high safety risk to operator increase the demand of the automatic process.



Figure 2.2 Manual and Automatic Disassembly Process Illustrations

The process requires a set of equipment most of which are specialized for particular type of munitions. Reverse assembly process primarily involves [2, 6];

- Removal of the initiating devices such as fuzes and igniters from the round
- Defuzing from the projectiles
- Separation of the boosters from the fuzes
- Removal of the igniters from the cartridge
- Removal of the energetic materials from the projectiles

Advantages of the automatic reverse assembly process are requirement of minimum personnel with low health hazard, high disassembly capacity and the current widespread use of the technology. Contrarily, required initial investment is high because of the mechanical systems [7].

2.1.2 Fluid Jet Cutting

In fluid jet cutting process, munitions were cut or sectioned by a high pressure fluid for disassembly. Munitions that cannot be disassembled by reverse assembly technique such as munitions in bad conditions or irregular shaped can be disassembled using

fluid jet cutting technique. Most of the time used fluid for the technique is water since the cases were cooled by water prohibits the possible source of ignition. Alternatively, other fluids such as liquid nitrogen and ammonia can also be utilized. Categorization of the fluid jet types are given in Table 2.1 below.

Table 2.1 List of the Fluid Jet Types

Type of Fluid Jet	Description
Fluid Jet	Fluids at a pressure of up to 410 MPa are driven through an orifice. Fluid jets have a high particle velocity, up to 1000 ms-1, and are capable of cutting various low-yield-strength materials directly without the need of extra abrasives.
Abrasive Fluid Jet	A fluid jet that, after accelerating the fluid through the orifice, aspirates abrasive particles and mechanically mixes them into the high-velocity fluid stream within a concentrating tube. Abrasive fluid jets may cut through practically any material depending on the abrasive and other variables. The most frequent fluid utilized is water, which is referred to as an Abrasive Water Jet (AWJ).
Abrasive Slurry Jet	A system that uses a combination of mixed fluid and abrasive slurry that is pressured and driven through a nozzle. Although abrasive slurry jets have the potential to be more efficient than abrasive fluid jets when operated at the same pressure, actual production equipment pressure levels are only approximately 20% of abrasive fluid jets, resulting in a proportionately lower efficiency. The difference between AFJ, in which the abrasive is combined at the nozzle, and ASJ, in which the abrasive is mixed at a distance from the nozzle.
Cavitating Fluid Jet	A water stream technique with a particular nozzle that causes natural creation of vapor bubbles in the fluid flow at an intermediate pressure of around 68 MPa. The start, growth, and impact of vapor bubbles on the target material

Type of Fluid Jet	Description
	are all part of the cavitating fluid jet process. The bursting of these vapor bubbles creates powerful, localized impacts that degrade the target material in a very varied way.



Figure 2.3 Water Jet Cutting Illustrations

According to the study of Miller and Munoz [8], water jets at 350 MPa are sufficiently safe in terms of impact sensitivity to use on high explosives and they made recommendations to mitigate the risk associated with water jet cutting operations. Although there are limited studies on the use of cavitating water jets for demilitarization, Summers et al. [9] claim that non-cavitating jets perform better in washout applications. Pressure, nozzle design, abrasive type, abrasive size, abrasive feed rate and rate of rotation of the munition are main parameters that determine the performance of water jet.

One of the main disadvantage of the water jet operations is creating a substantial amount of contaminated water despite the low flow rates resulting from the high pressures utilized. The water contaminated by the energetic material can be recovered and filtered before reused [10, 11], yet it must eventually be disposed by treatment [12]. Furthermore, emulsions formed by water with energetic materials can be hazardous and disposal of them can be tough. Possibility of explosive and pyrophoric hazards can also be present in water jet operations depending on the type of the energetic material.

Other fluids have been investigated as a result of these disadvantages, yet neither are as frequently used and researched as water.

2.1.3 Cryofracturing

The use of a liquid nitrogen bath to make munitions more brittle, which are subsequently shattered in a hydraulic press, is known as cryofracture. The munitions are safe for further processing (such as incineration) once they have been fractured since the possibility of a high-order event has been eliminated.

Disassembly operations of small or medium sized high explosive munitions such as mines, hand grenades etc. are difficult. Moreover, after applying traditional mechanical methods to these items, there is still a risk of detonation. Thus, use of cryofracture technique is advantageous for these type of munitions. The presence of an explosive-containment chamber ensures safety in the case of a detonation [13].

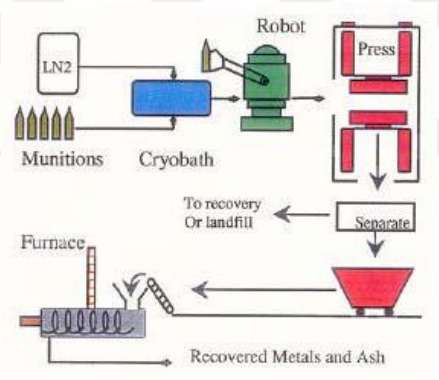

Figure 2.4 Cryofracture Process Diagram [14]

2.1.4 Cryocycling

The use of liquid nitrogen to portion propellant to uniform sizes for disposal or reuse is known as cryocycling. It plays a major role in the demilitarization of rocket engines.

According to the study of Sandia National Laboratories, contact with liquid nitrogen creates a stress gradient which result formation of cracks, if the stresses surpass the material strength. Additional fractures appear when the temperature returns the normal. Size reduction is increased as multiple cycles were applied even though the reduction rate for one cycle is decreasing. Sandia found that three to four cycles is

sufficient to reduce bulk double base (NC/NG) propellants to fragments of 6-10 mm in size [15].

One advantage of the cryocycling is that this technique does not contribute waste product since the nitrogen is inert. Energetic materials obtained from cryocycling are feasible to reuse since the process has very little effect on quality of the material.

2.1.5 Ultrasonic

Ultrasonic pulses are used to fracture cast-loaded energetic materials in this process. Ultrasonic pulses promote cavitation in the liquid, causing dissociation in a submerged material. The technique is in research phase and it is potentially cost effective and environmentally friendly.

2.1.6 Femtosecond Laser Cutting/Laser Machining

Roeske showed the ability to ablate metals and energetic materials using a femtosecond laser [16]. The material is ablated with almost negligible heat transmission to the surrounding material, resulting in a cold laser cutting process since the absorption of the ultra-short laser pulse proceeds over such a short time scale. Another study claimed that a continuous wave laser might be utilized since it induces vaporization, which evacuates heated high explosive before bulk ignition [17].

This technique might potentially provide a way to remove explosives without producing waste, although the technique is still in its development stage. Main disadvantages are limited capacity, significant investment cost to purchase equipment and the requirement for highly qualified personnel to run and maintain such complicated equipment.

2.2 Removal

The main objective is to remove energetic material from the disassembled munition for reusing or destroying the recovered material.

2.2.1 Meltout

Meltout systems utilize a number of methods to heat the energetic material in a munition in order to force it out of the casing. Filling holes are frequently inadequate for removal and may not be used by the time a munition is demilitarize, requiring some type of reverse engineering or cutting.

Meltout is used to discharge of cast high explosives such as TNT and Comp-B. Compositions that are difficult to melt, such as RDX and HMX, will not work, and liner materials may create issues. There are two types of meltout techniques which either employ pressurized hot water or steam to melt the filler or use indirect methods such as microwave and induction meltout.

In steam meltout technique, meltout of energetic material is provided by steam or hot water jets. This technique produces a lot of waste water because of the low temperature and pressure.

In microwave meltout technique, meltout of energetic material is provided by microwaves. There are several benefits of microwave meltout. Firstly, the energetic material is not exposed to water or steam in this technique so that high-purity materials can be produced to reuse. The lack of water also prevents the formation of hazardous wastes. This technique may also be more energy efficient than conventional meltout procedures since the energy is transmitted directly to the energetic material. Yet, there is not any plant that used microwave meltout. Furthermore, care needs to be taken to ensure safety operation due to absence of water.

In autoclaves, water is heated over the boiling point in a pressurized vessel to melt a cast explosive, which is subsequently collected for treatment or destruction. Generated waste water is reduced since autoclave can only apply steam to the outside of the munition. One disadvantage of autoclave meltout is having long processing time for larger munitions.



Figure 2.5 Autoclave Meltout Illustration

In induction meltout technique, induction is applied to a munition's case to melt the cast explosive for recovery or treatment. One of the main disadvantage of this technique is its tendency for developing "hot spots" in metal casings, which might lead to instantaneous fires or explosions. It's also important to avoid sparking between the inductive coil and the casing.

2.2.2 Washout

The energetic materials in the munition casing can be removed using a high-pressure water jet. In contrast to water jet cutting, an abrasive in the water is not usually required. Advantages over standart meltout techniques are given as;

- less time required to remove the explosive from the projectile
- applicable to all explosives, including PBX
- less energy required compared to melt-out
- less environmental contamination since the water is reused
- less TNT vapor, resulting in a lower health risk to personnel in the building
- removal is more efficient

There are certain disadvantages to this method such as generation of waste water, risks associated with the compounds' explosive qualities and their capabilities of combustibility.

Liquid nitrogen and carbon dioxide can also be used instead of the water.



Figure 2.6 Water Jet Washout Illustration

2.2.3 Dry Ice Blasting

This technique eliminates impurities from the surface of obsolete munitions. Cryogenic cleaning sprays a supersonic stream of solid CO_2 particles onto the cleaning area. With low contact abrasion, the force is adequate to remove impurities. Friction delays the dry ice pellets as they penetrate the contaminant and strike the substrate, causing them to warm up. The pellets quickly sublimate as they warm up. The contaminant, which is no longer stably attached, is forced to be expelled from the substrate by the expansion. Although dry ice blasting is an excellent way for eliminating surface pollutants, it is not a common practice.



Figure 2.7 Dry Ice Blasting Illustration

2.3 Destruction

Destruction is used to have a completely non-energetic end product by using thermal or chemical techniques. The energetic materials are often transformed mainly into combustion gases. There are three types of technology for destroying energetic materials: confined or unconfined destruction, thermal destruction, and chemical destruction.

2.3.1 Open Burning and Open Detonation

To eliminate unserviceable, unstable Unexploded Ordnance (UXO) or obsolete weapons and explosive materials, open burning and open detonation (OB/OD) activities are carried out. It is the cheapest and most technologically easy technique of disposal accessible. Self-sustained combustion, which is started by an external source such as flame, heat, or a detonation wave, is used in OB operations to eliminate explosives or munitions. Detonable explosives and munitions are eliminated in OD operations by an explosion triggered by a disposal charge. OB/OD operations can detonate a variety of explosives, pyrotechnics, propellants and other energetic materials. Unless the nature of the materials involved allow for orderly burning without explosion, OB zones must be able to withstand unexpected detonation/deflagration of any or all explosives being destroyed.



Figure 2.8 Illustration of OB/OD

Electric or flame ignition methods can be used to start OB and OD. Electric methods are preferred in general because they provide for greater control over the time of the activation. Electric current warms a bridge wire, which ignites a main explosive or pyrotechnic composition, which further ignites or detonates the material to be burnt or detonated in an electric system. Safety fuzes are used to start the burn or explosion when required [18].

Although OB/OD can successfully destroy munitions, they fall short of the cost-effective issue of eliminating waste by-products. Such disposal procedures are unsuitable for the environment since they pollute the ecosystem. OB/OD, for instance, creates relatively high quantities of undesired environmental pollutants such as nitrogen oxides (NOx), acidic gases, various forms of particles, including metal, as well as a variety of pollutants on the soil surface (metals, explosive residues, and combustion by-products). However, it is thought that fulfilling emission criteria for the destruction of certain weapons is achievable, with OD being a cleaner approach [19, 20].

However, incomplete combustion products from the burning pits utilized for OB techniques can leak into the soil and harm ground water. To fulfill environmental criteria, the surrounding soil and ground water are frequently treated following OB/OD. Due to increasingly strict national and also other environmental protection regulations [21], as well as the limited availability of incineration sites and the hazards associated with transportation of large quantities of propellants or explosives [22], OB/OD for munitions disposal has become unsuitable. Furthermore, these procedures result in losses not only from the waste of precious resources, but also from the high expenses of transportation to the destruction site and the demolition activity itself [23]. The noise generated by open detonation, especially, is difficult to reduce. As a result of all of these issues, it is widely acknowledged that a significant decrease in environmental emissions from open burning is required, as well as the development of more ecologically friendly demilitarization methods [24].

2.3.2 Contained Burning

Ignition of rocket motors in a contained chamber is utilized in this technique. Upon the burning, the vessel's contents are processed through a pollution abatement system to make sure that emissions regulations are satisfied.



Figure 2.9 Illustration of Contained Burning

The technique offers a variety of benefits such as not to be classified as incinerator making approvals easier since the process does not use a burner, being transportable and reduced usage of energy.

Since the technique is a batch procedure, it is not suitable for major demilitarization projects. Usage of the technique is limited with rocket motors and it would need some testing at higher pressure in the containment vessel for safety issues.

2.3.3 Contained Detonation

Detonation by a donor charge in a contained chamber is provided. The demolition is accomplished in a single step operation. The chamber is built to resist the pressure of explosion and fragmentation. An expansion tank prevents the overpressure and emissions controlled by a pollution abatement system.



Figure 2.10 Illustration of Contained Detonation

The technique is advantageous when used site cleanup operations to destroy UXO on-site with controlled emissions in case mobility of UXO is allowed. Another benefit of the technique is to destruct experimental or prototype munitions when the number and diversity make demilitarization on an industrial basis impractical. It can also be used for destructing munitions which have potential risks arising from disassembly or OB/OD operations such as non-stockpile chemical munitions.

The technique is a small capacity batch process; thus it is not suitable for major demilitarization projects.

2.3.4 Incineration

Incineration technique decomposes the energetic waste by heating. Although the phrase incineration can refer to a variety of thermal treatment process, such as open and enclosed burning, it is most commonly used to refer to a controllable and enclosed treatment that uses an external source of heat. Thermal treatment, thermal destruction, and thermal disposal are other terms used to describe incineration.

For the disposal of energetic materials, various incineration systems are already in use: rotary kiln, fluidized bed incinerator, plasma arc thermal treatment, flash furnace, and deactivation furnace. Toxic gases, including as HCN, NOx, HCl, and soot are always created in significant amounts during the combustion of energetic materials, necessitating a complex and costly fume cleaning operation. Some incineration units are mobile and may use the waste energy to generate heat or power.

2.3.4.1 Rotary Kiln

The rotary kiln is the most widely used form of energetic material incineration. It is typically comprised of multiple chambers which is insulated as in standart furnace or

armored to withstand detonations and fragmentation. The kiln is slightly inclined to horizontal and rotates gradually over time around its axis. After loading the energetic material to be treated into cylinder's top end, the material slowly passes down towards the bottom end of the kiln as it rotates, and it may be stirred and mixed. The energetic wastes are burned when hot gases move through the kiln. Conveyors and feeder equipment are included in most furnaces, as well as pollution abatement systems to regulate gaseous pollutant emissions. An afterburner, a dry scrubber, a cyclone particle separator, a gas cooling system, and a filter are examples of typical equipment. Thermal decomposition furnaces operate at temperatures ranging from 650° to 820°C [46].

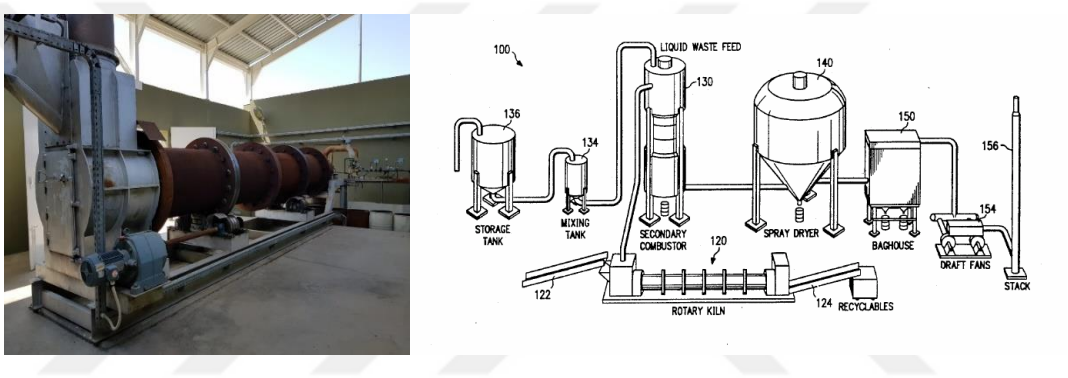

Figure 2.11 Rotary Kiln Illustration

The rotary kiln is particularly well suited to the destruction of a diverse variety of munition types such as bulk propellants, small arms and small detonable items. Depending on the wall thickness of the rotary kiln, it may have capability of high explosive processing. Size of small arms and small detonable items to be processed are also determined by the kiln's wall thickness.

2.3.4.2 Static Kiln

Static kilns are insulated chambers that may be heated to generate deflagration or detonation of the materials using indirect heating instead of adding more gas to the output. Since the static kiln does not contain a donor charge to generate detonation as in controlled detonation technique, the sole impact is either burning or deflagration.



Figure 2.12 Static Kiln Illustrations

Static kiln is a viable system that can be used as an alternative for the rotary kiln. Incineration of small quantities of high explosives or propellants can also be utilized.

2.3.4.3 Fluidized Bed Incinerator

In fluidized bed incinerator, the energetic material waste is fed as a non-detonable slurry (concentration of approximately 50% of the explosive weight) [10] into the bed which composed primarily particular sized mixture of sand and coal particles [47]. Sand particles begin to float and behave like a liquid as a result of the heated air flow. This technique is safe and ecological friendly for incineration of the energetic materials.

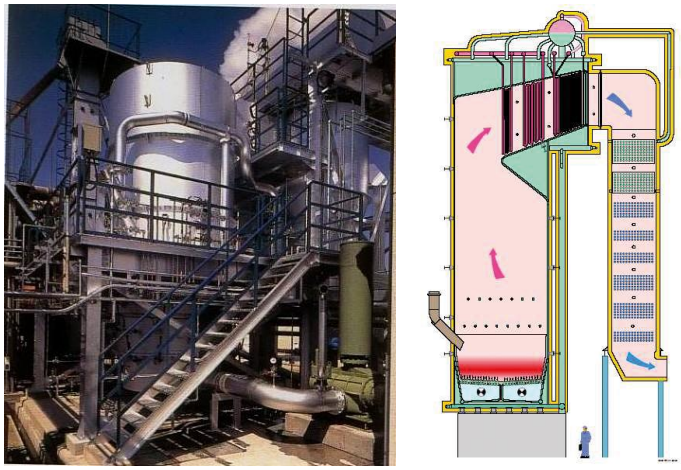

Figure 2.13 Fluidized Bed Incinerator Illustration

The fluidized bed incinerator's main benefit is its low energy usage which is also allows the excess heat from the incinerator to be used to heat a second furnace. Fluidized bed incinerators have a great scope for controlling the combustion

efficiently. Reaction of excess air with explosives in small amount release reduced emissions.

Due to the creation of compounds that would react with the bed's sand particles, disposal of pyrotechnic compositions by means of fluidized bed incineration is not always practicable. The technique is inefficient for the small caliber munitions and munition parts since it requires too much work force.

2.3.4.4 Flash Furnace

This technique is utilized to flash metal scrap contaminated with small amounts of explosives or incinerate small caliber ammunition parts such as igniters, detonators and fuzes. In most cases, the furnace is utilized in conjunction with another furnace. Thus, required heat is generally supplied by the excess heat of the other furnace. The furnace is made up of a stationary heat - resistant lined furnace and a car, which is usually rail mounted for external loading and subsequently placed in the furnace.



Figure 2.14 Flash Furnace Illustration

The technique is intrinsically safe, highly configurable, extensively used and demonstrated. The method is a batch process with a limited capacity.

2.3.4.5 Plasma Arc Thermal Treatment

In this technique, a plasma arc between two electrodes or between an electrode and the ground at temperatures developed up to 11000 °C. The technique has a specific role in the demilitarization of obsolete or unserviceable small, assembled pyrotechnic

munitions which are hard to destruct using OB/OD or regular incineration considering formation of a considerable volume of particle matter and local temperature hot spots.

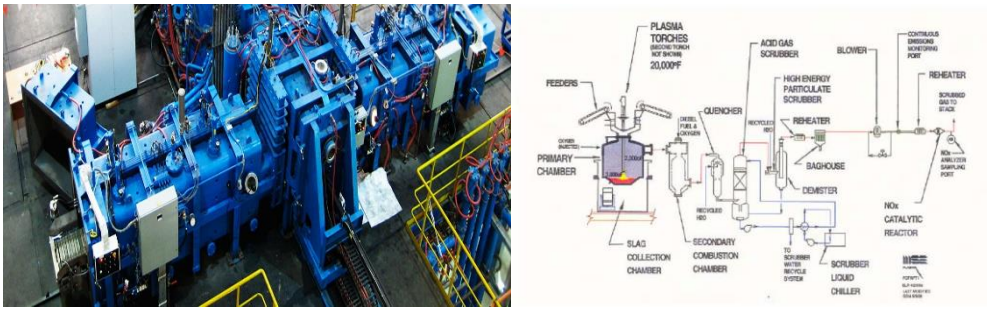

Figure 2.15 Plasma Arc Thermal Treatment

Plasma arc procedures produce more relatively harmless pollutant streams as relative to furnaces, yet their capability to treat detonable materials is restricted. The technique requires high amount of investments for bulk energetics.

2.3.4.6 Molten Metal Pyrolysis

In the pyrolysis reaction, organic compounds are decomposed by heat in the lack of oxygen. The technique uses metals at approximately 1650 °C and generates environmental pollutants and a slag [48].

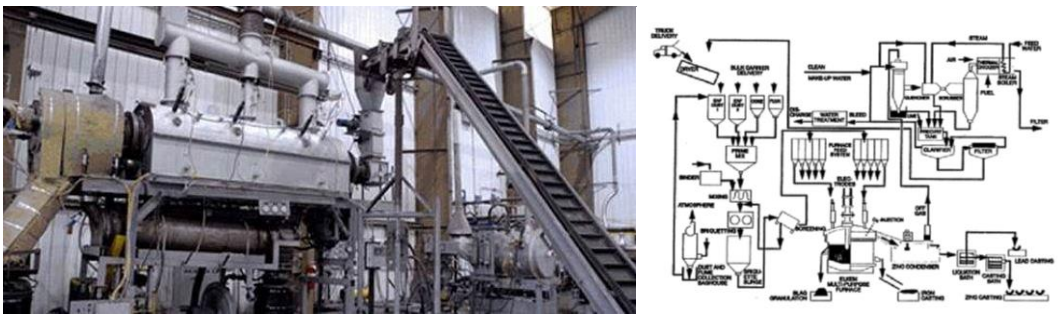

Figure 2.16 Process Flow of Molten Metal Pyrolysis

Even though it is quite effective in destroying organic waste, the exhaust gases still need to be treated, and the operating conditions are difficult and costly to establish.

2.3.4.7 Pollution Abatement Systems

Incineration operations might be equipped with a Pollution Abatement System to ensure that they fulfill national emissions requirements. Pollution Abatement Systems

must fulfill legal temperature requirements and manage a variety of contaminants including VOCs, particulate matter, acidic gases, heavy metals, dioxins and furans.

The installation of an afterburner or secondary combustor just after the furnace allows facilities to satisfy the temperature standards set out by EU regulations. Afterburners /secondary combustors usually run at a temperature of 1200-1700 °C, which is hot enough to eliminate VOC and minimize the development of dioxins/furans. Carbon dioxide, water, and acidic gases are formed from VOCs. In order to limit the generation of NOx, ammonia can be supplied during the afterburning process.

After the afterburner, a method to cool the combustion products is required to avoid damage to the rest of the system. Undesirable heating of metal parts might cause damage, as well as the possibility of fires. Baghouse filtration systems are especially vulnerable to fire. Water spray is commonly used to cool the gas, lowering the temperature to roughly 500 °C. In order to reclaim some energy from the process, an excess heat boiler might be used. A scrubber system is essential to extract the acidic gases. For eliminating and neutralizing NOx and SOx, the scrubber utilizes water with an alkaline salt added.

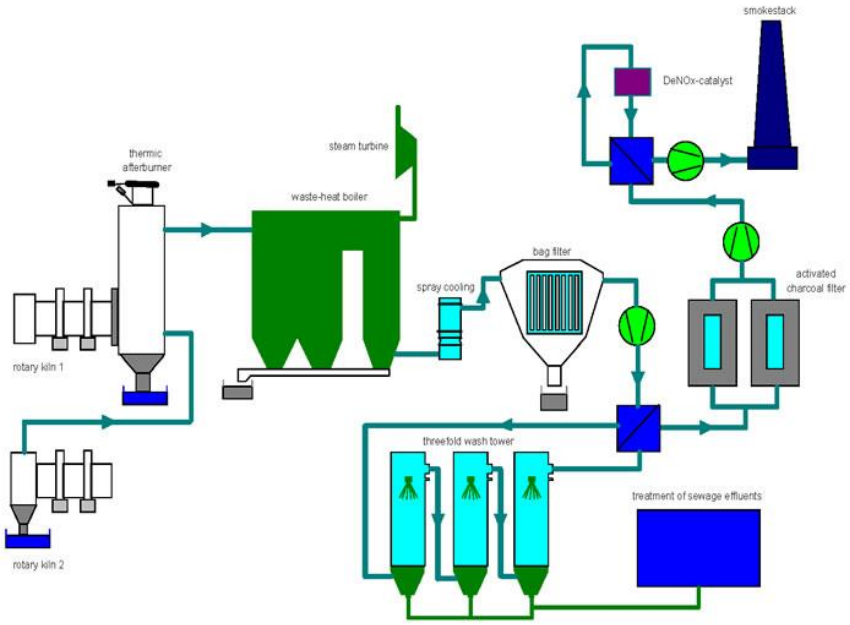

Figure 2.17 Schematic Diagram of a Pollution Abatement System [20]

There are three basic types of scrubbers, each of which has a different influence on the liquid in the gas stream. In venturi system, a venturi nozzle is used to accelerate the exhaust gases, after which the liquid is injected and atomized, resulting in effective waste gas scrubbing. Packed systems produce turbulence and mixing of the liquid and gas using customized particles in a column. Spray system operates by spraying liquid droplets into the flue gas to remove acidic gases.

A dry ceramic filtration system or a less expensive baghouse system containing Gore-Tex/Teflon filter bags may both remove particles. The dry ceramic system is more effective and decrease the possibility of fire. An activated charcoal bed can be utilized to absorb heavy metals, particularly mercury, and any residual VOC from the flue gas. Pollution Abatement Systems may also have a monitoring system to assure that environmental standards are reached.

CHAPTER 3

MATHEMATICAL MODELS AND SIMULATION

3.1 Water Ejector Model Specifications

After design considerations of selecting the greener disposal system from the literature/available technology, another selection criterion emerges. Due to the high stored chemical energy, critical process points of energetic materials should be investigated in order to achieve safety operation.

Sensitivity can be described as energy level required for an energetic material to respond varying external stimuli such as impact, friction, electrostatic discharge and heat. Despite understanding the flow behavior of energetic material is critical for their safe usage, it has been detected during the literature review that there was surprisingly limited research on explosive rheology.

Study of Parry et al. stated that transition from laminar flow to turbulence during dynamic loading of TNT may give rise to "hotspot" temperatures sufficient for ignition [25]. According to study conducted by Burkhardt et al. [26], viscosity of TNT is dependent on the temperature and best represented by following formula;

$$log\mu = A + B/T + C/T^2 \quad (3.1)$$

where μ was the viscosity in centipoise (cP), T was the temperature in degrees Kelvin and A=2.78, B=-2810, C=7.8*10^5. Besides, conducted work of Parry et al. [25] showed that study of Burkhardt et al. has errors and temperature dependency of the TNT viscosity can be described sufficiently by an Arrhenius type equation as given below;

$$\mu = Ae^{B/T} \quad (3.2)$$

where A=0.00346 cP and B=3720 K.

Various studies claimed that TNT is more sensitive to initiation when it's in the molten state [27-29]. Therefore, meltout by steam technique was selected for analysis.

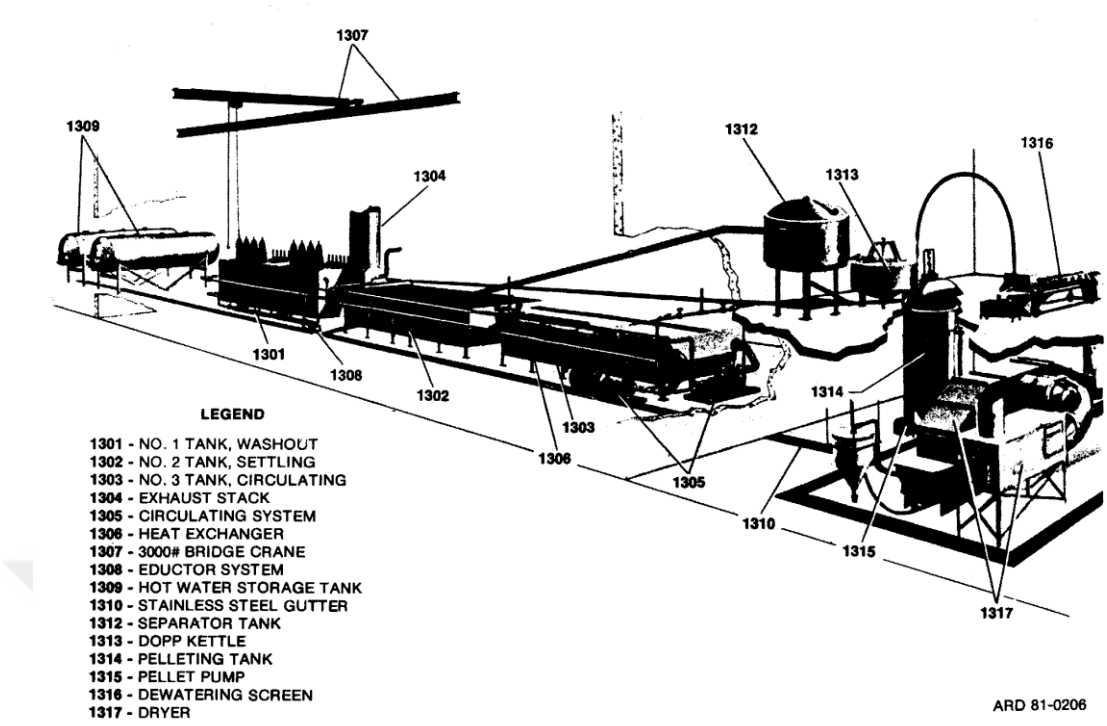

Figure 3.1 Schematic Diagram of Explosive Washout Plant [30]

In order to select an analysis point, possible operation areas that has high turbulence intensity were predicted as mixture transfer by water ejector, opening and closing operations of valves and mixing operation in Dopp Kettle. Since the velocity magnitude of mixing operations were small compared to water ejector, water ejector is selected as the analysis component.

Ejectors whose working principle is based on momentum transfer from a high-pressure flow to a low-pressure flow are mechanical devices which have a nozzle, a suction chamber, a mixing section, and a diffuser as its primary components [31]. Ejectors were useful equipment due to absence of moving parts, exclusion of lubricants and bearings, high dependability and minimal installation cost [32-34].

TM 9-1300-277 Technical Manual states that process temperature of hot water washout system should be held at approximately 82-96 °C [30]. Thus, operation temperature range was selected as 82-96 °C.

Structure and size of the analyzed ejector is shown in Figure 3.2 and Figure 3.3, respectively . Dimensions of the ejector are given in Table 3.1.

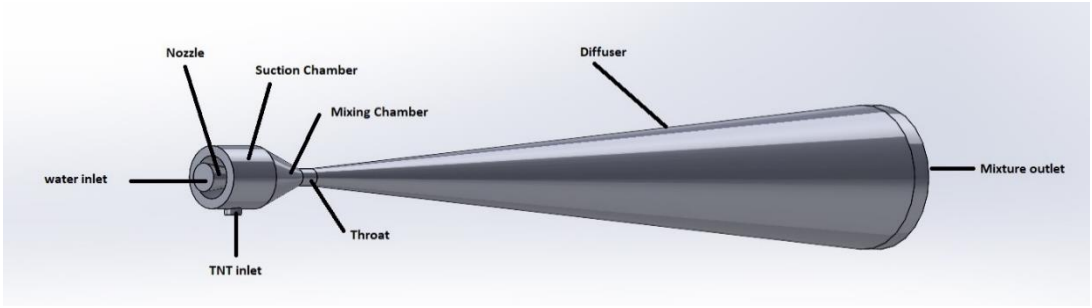

Figure 3.2 3D View of the Water Ejector

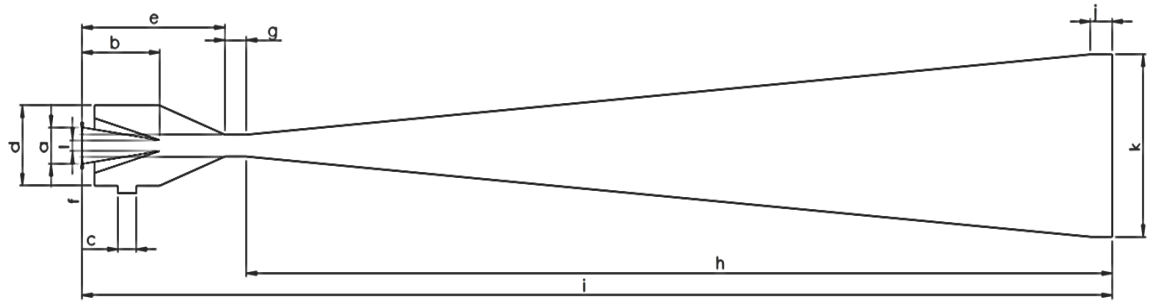

Figure 3.3 Size of the Water Ejector

Table 3.1 Dimensions of the Water Ejector

Geometry Definition	Parameter	Dimension (mm)
Inlet Diameter of Primary Flow	a	10
Nozzle Length	b	25
Inlet Diameter of Secondary Flow	c	6
Suction Chamber Diameter	d	22
Length Between Nozzle and Throat	e	42
Diameter of Throat	f	6
Throat Length	g	7
Diffuser Length	h	279
Ejector Total Length	i	332
Outlet Straight Length	j	7
Diameter of Diffuser Outlet	k	50
Nozzle Diameter	l	3

3.2 Mathematical Modelling

Theoretical mathematical modeling may be useful in understanding the complicated nature of the flow inside ejectors. Although ejectors have a three-dimensional internal flow field, one-dimensional (1D) mathematical techniques can help with system operation, interpretation of experimental data, and system design and optimization [35].

The compressible transient-state turbulent version of the Eulerian-Eulerian two-fluid mixture model governs the flow within the ejector [36]. The continuity equations for the mixture are;

$$\frac{\partial \rho_m}{\partial t} + \nabla \cdot (\rho_m u_m) = 0 \tag{3.3}$$

$$u_m = \frac{\sum_{r=1}^{n} \alpha_r \rho_r u_r}{\rho_m} \tag{3.4}$$

$$\rho_m = \sum_{r=1}^{n} \alpha_r \, \rho_r \tag{3.5}$$

$$\frac{\partial \alpha_r \rho_r}{\partial t} + \nabla \cdot (\alpha_r \rho_r u_m) = 0 \tag{3.6}$$

where t is time in s, ρ_m is the mixture density in kg/m^3, u_m is the mixture velocity vector in m/s, α_r is the volume fraction of phase r, ρ_r is the density of phase r in kg/m^3, u_r is the velocity vector of phase r in m/s.

The momentum equations for the mixture are;

$$\frac{\partial}{\partial t}\rho_m u_m + \nabla \cdot (\rho_m u_m u_m) = -\nabla p + \nabla \cdot \left[\mu_m \left(\nabla u_m + \nabla {u_m}^T\right)\right] + \rho_m g + F \tag{3.7}$$

$$\mu_m = \sum_{r=1}^{n} \alpha_r \, \mu_r \tag{3.8}$$

where ∇p is the pressure gradient in Pa/m, μ_m is the viscosity coefficient of the mixture in Pa·s, g is the gravitational acceleration in m/s^2, F is the volume force in N/m^3.

The energy equations for the mixture are;

$$\frac{\partial}{\partial t}\sum_{r=1}^{n}(\alpha_r \rho_r E_r) + \nabla \cdot [\rho_r u_r (\rho_r E_r + p)] = \nabla \cdot \left(k_{eff} \nabla \mathrm{T}\right) + S_E \tag{3.9}$$

$$E_r = h_r - \frac{p}{\rho_r} + \frac{u_r^2}{2} \tag{3.10}$$

where E_r is the mechanical energy per unit mass in J/kg, p is the static pressure in Pa, k_{eff} is the effective conductivity in W/m·K, T is temperature in K, S_E includes any other volumetric heat source in J, h_r is the sensible enthalpy for phase r in J/kg.

In CFD analyses of ejector performance, turbulence models have recently been considered. Turbulence is simulated for single-phase ejector flow using the SST k–ω model, which estimates the position and structure of the shock-wave better than a classical *k–ε* model according to the studies conducted by Croquer et al [37,38]. However, when it comes to two-phase ejector flow, the classical *k–ε* model produces satisfactory results as compared to experiments. In a supersonic ejector, Gagan et al. [39] employed particle image velocimetry (PIV) to establish the optimal turbulence model for flow behavior prediction. The experimental findings were compared to the results of the CFD simulation and the CFD findings with the classical *k–ε* model were found to be the most similar to the PIV results. As a result, the standard *k–ε* turbulence model equation is selected to be applied in this study. Equations are given as follows;

$$\frac{\partial}{\partial t}\rho_m u_k + \frac{\partial}{\partial x_i}\rho_m k u_m = \frac{\partial}{\partial x_j}[(\mu_m + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}] + \tau_{ij}\frac{\partial u_m}{\partial x_j} - \rho_m \varepsilon \tag{3.11}$$

$$\frac{\partial}{\partial t}\rho_m \varepsilon + \frac{\partial}{\partial x_i}\rho_m \varepsilon u_m = \frac{\partial}{\partial x_j}[(\mu_m + \frac{\mu_t}{\sigma_\varepsilon})\frac{\partial \varepsilon}{\partial x_j}] + C_{1\varepsilon}\frac{\varepsilon}{k}\tau_{ij}\frac{\partial u_m}{\partial x_j} - C_{2\varepsilon}\rho_m\frac{\varepsilon^2}{k} \tag{3.12}$$

$$\mu_t = \frac{\rho_m C_\mu k^2}{\varepsilon} \tag{3.13}$$

where k is the turbulence kinetic energy in m^2/s^2, μ_t is the turbulence viscosity in Pa·s, τ_{ij} is the turbulence stress tensor in Pa, ε is the turbulence dissipation rate in m^2/s^3, $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_\mu = 0.09$, $k = 1$ and $\varepsilon = 1.3$.

Heating coefficient θ is;

$$\theta = \frac{T_m - T_p}{T_p} \tag{3.14}$$

where T_m is the mixture outlet temperature in K, T_p is the primary fluid inlet temperature in K.

Pressure ratio P_{rt} is;

$$P_{rt} = \frac{P_m}{P_s} \tag{3.15}$$

where P_m is the mixture outlet pressure in Pa, P_s is the secondary inlet pressure in Pa.

3.3 Computational Fluid Dynamics (CFD) Modelling

The Computational Fluid Dynamics (CFD) approach, which uses numerical solutions to offer a comprehensive description of the flow field inside ejectors, is another alternative for ejector modeling. The CFD technique has been shown to be an effective tool for resolving some of the difficulties of 1D mathematical techniques [40]. CFD has recently been utilized to correctly evaluate the impact of friction loss coefficients and ejector configuration on performance [41-43], as well as to analyze the flow distribution inside ejectors.

Structure and size of the analyzed ejector is shown in Figure 3.2 and Figure 3.3, respectively . Dimensions of the ejector are given in Table 3.1. In this study, primarily inlet fluid was selected as water. In order to reduce simulation complexity and increase safety level of the process, secondary inlet fluid was selected as molten TNT in spite of the fact that most of the time fluid has small fraction of water. Figure 3.4 illustrates the water ejector's main meshes. Mesh information is given below in Table 3.2.

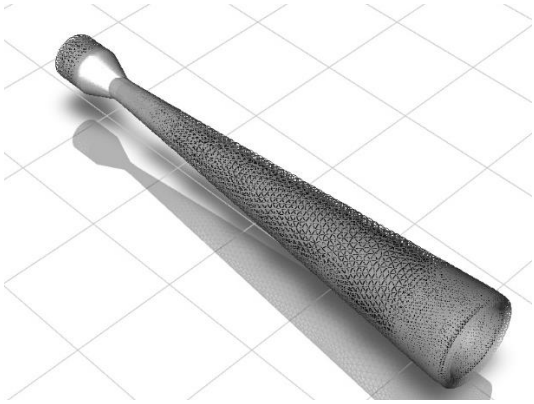

Figure 3.4 Main Meshes of Water Ejector

Table 3.2 Mesh Information of the Analysis

Description	**Value**
Node Number	66786
Cell Number	352804
Face Number	720210
Element Number	352804
Element Type	Polyhedral
Minimum Face Angle (degree)	12.2491
Maximum Face Angle(degree)	147.999
Maximum Edge Length Ratio	4.07052
Maximum Element Volume Ratio	142.784
Maximum Element Volume (m^3)	$2.067 \cdot 10^{-7}$

The commercial program ANSYS Fluent 21.2 is utilized as the CFD solver in this study. The simulation is executed with a three-dimensional double-precision and pressure-based, transient, mixture multiphase model, implicit solver, standart k–ε model with energy equation.

Fluid materials were water liquid and TNT. Water liquid material properties were inserted from default CFD fluid database. Since the material properties of the TNT has not been found on the CFD database, it was created manually. Material properties of the TNT created in the solver is given below in Table 3.3.

Table 3.3 Material Properties of TNT Fluid

Property Name	Value	Unit
Density	1654	kg/m^3
Specific Heat (Cp)	1062.2	J/(kg.K)
Thermal Conductivity	0.26	W/ (m.K)
Molecular Weight	227.13	Kg/kmol
Standard State Enthalpy	-63.2	J/kgmol
Reference Temperature	298.15	K

Viscosity of the TNT was defined as a function as given in Equation 3.2. Viscosity values for variable temperatures are shown in Table 3.4 below.

Table 3.4 Calculated Viscosities of TNT for Variable Temperatures

Temperature (K)	Viscosity (Pa.s)
355	1,230E-01
356	1,195E-01
357	1,160E-01
358	1,127E-01
359	1,095E-01
360	1,064E-01
361	1,034E-01
362	1,005E-01
363	9,766E-02
364	9,494E-02
365	9,232E-02
366	8,979E-02
367	8,734E-02
368	8,496E-02
369	8,267E-02

CHAPTER 4

RESULTS AND DISCUSSION

The commercial program ANSYS Fluent 21.2 is used as the CFD solver to investigate rheological characteristics of the flow. Specific temperature points selected within the operation range as 355 K, 359 K, 364 K and 369 K. Results and discussions are given in separate sections for each specific point. A general evaluation is made in the discussion section.

4.1 Results for 355 K Inlet Temperature

Velocity distribution at 355 K inlet temperature is given in Figure 4.1. As seen from the Figure 4.2, maximum velocity occurs in the mixing chamber as 2,346031 m/s.

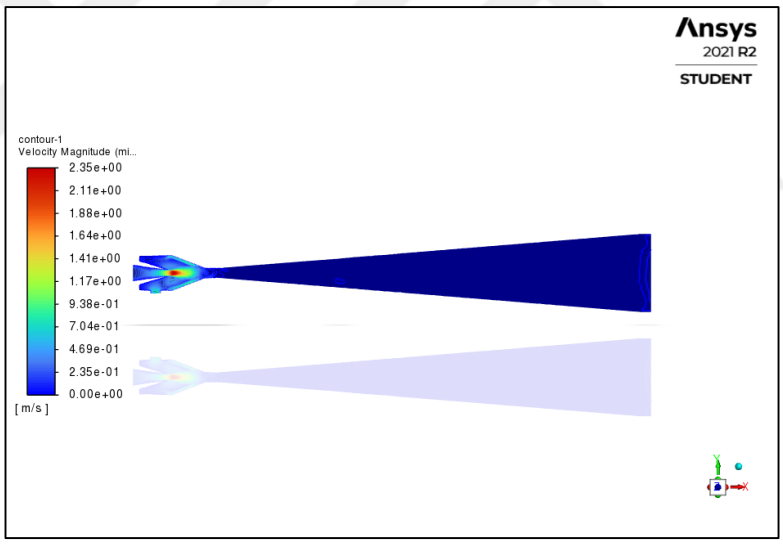

Figure 4.1 Velocity Distribution at 355 K

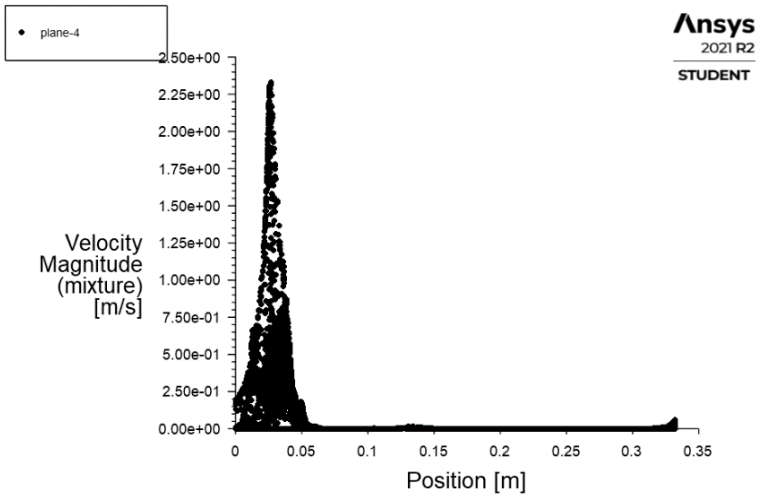

Figure 4.2 Velocity Position Distribution at 355 K

Turbulent kinetic energy of water ejector at 355 K inlet temperature is shown in Figure 4.3. Maximum value of the turbulent kinetic energy was found as $4.36 \cdot 10^{-2}$ J/kg as seen from the Figure 4.4.

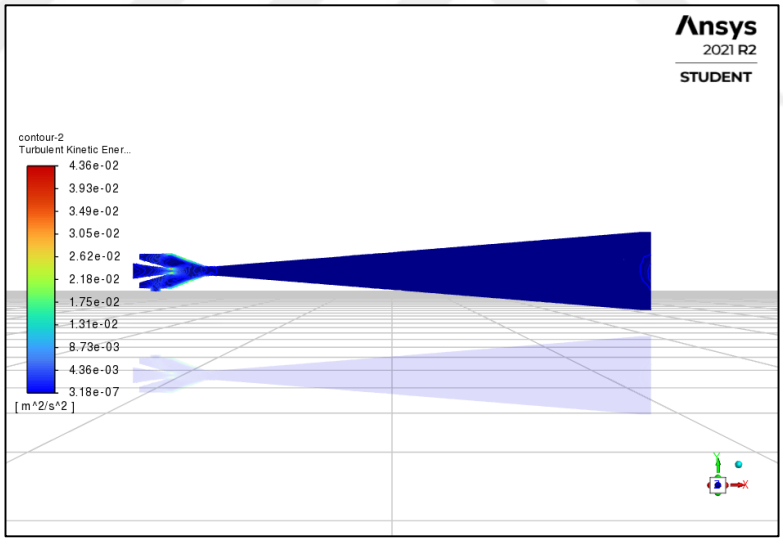

Figure 4.3 Turbulent Kinetic Energy Distribution at 355 K

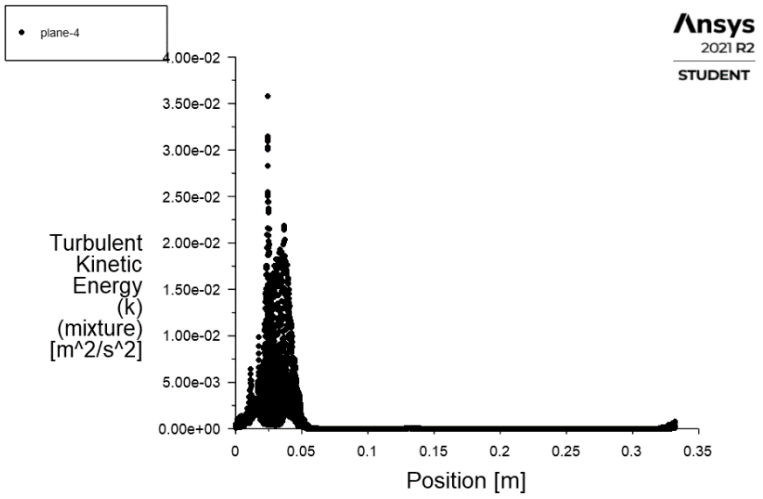

Figure 4.4 Turbulent Kinetic Energy Position Distribution at 355 K

4.2 Results for 359 K Inlet Temperature

Velocity distribution at 359 K inlet temperature is given in Figure 4.5. As seen from the Figure 4.6, maximum velocity occurs in the mixing chamber as 2,353232 m/s.

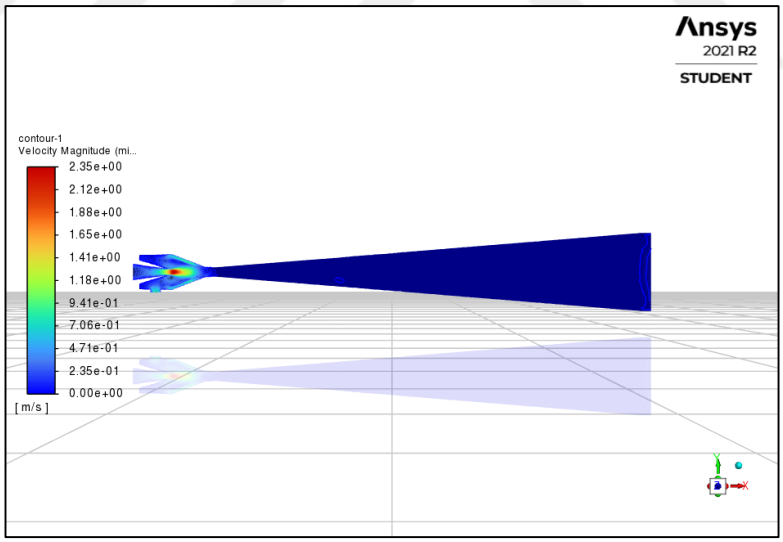

Figure 4.5 Velocity Distribution at 359 K

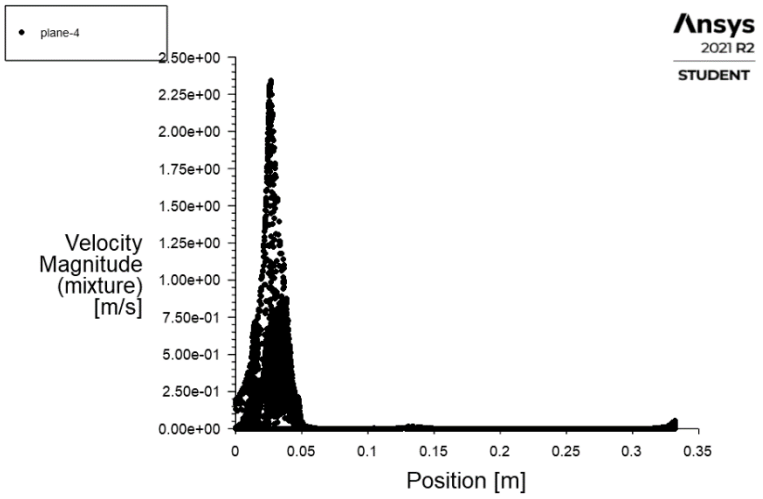

Figure 4.6 Velocity Position Distribution at 359 K

Turbulent kinetic energy of water ejector at 359 K inlet temperature is shown in Figure 4.7. Maximum value of the turbulent kinetic energy was found as $4.37 \cdot 10^{-2}$ J/kg as seen from the Figure 4.8.

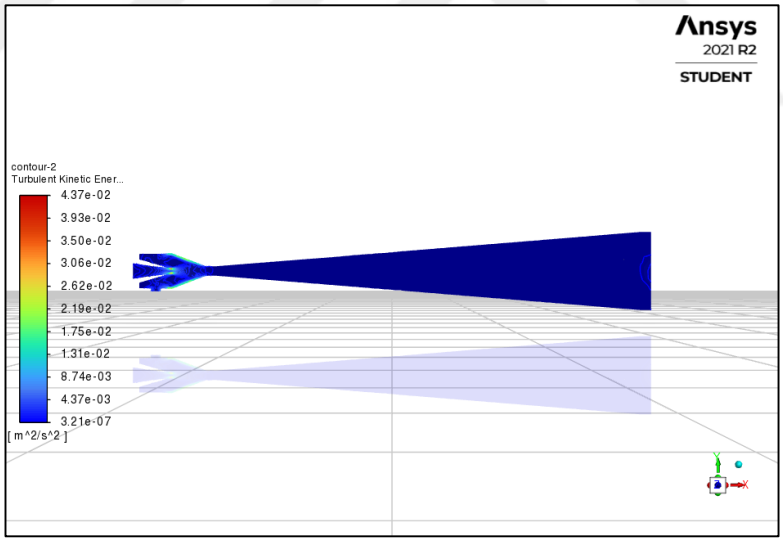

Figure 4.7 Turbulent Kinetic Energy Distribution at 359 K

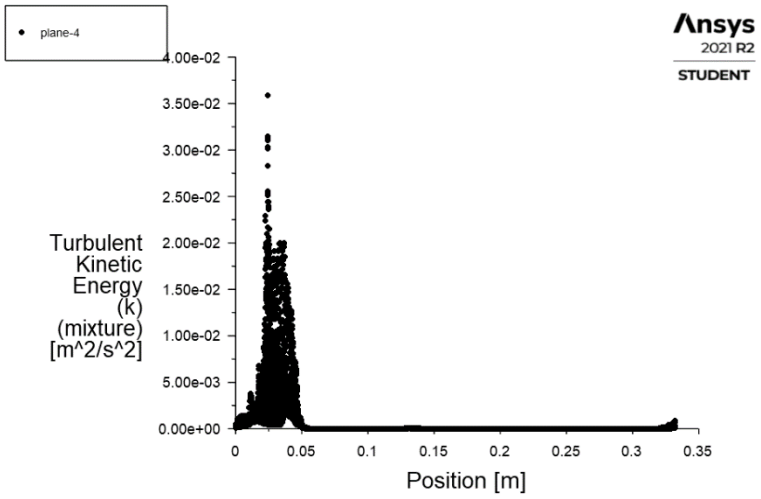

Figure 4.8 Turbulent Kinetic Energy Position Distribution at 359 K

4.3 Results for 364 K Inlet Temperature

Velocity distribution at 364 K inlet temperature is given in Figure 4.9. As seen from the Figure 4.10, maximum velocity occurs in the mixing chamber as 2,355863 m/s.

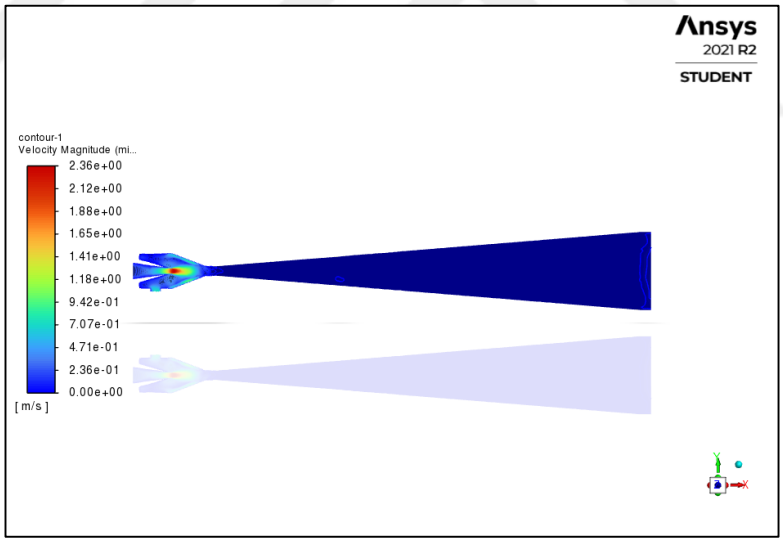

Figure 4.9 Velocity Distribution at 364 K

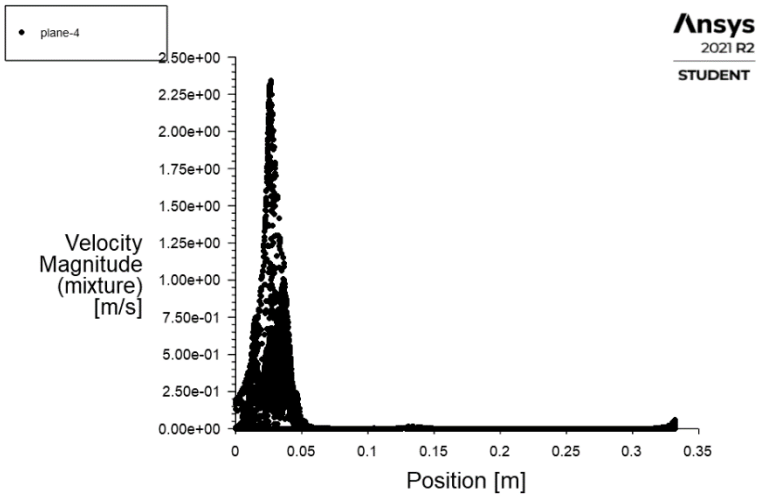

Figure 4.10 Velocity Position Distribution at 364 K

Turbulent kinetic energy of water ejector at 364 K inlet temperature is shown in Figure 4.11. Maximum value of the turbulent kinetic energy was found as $4.37 \cdot 10^{-2}$ J/kg as seen from the Figure 4.12.

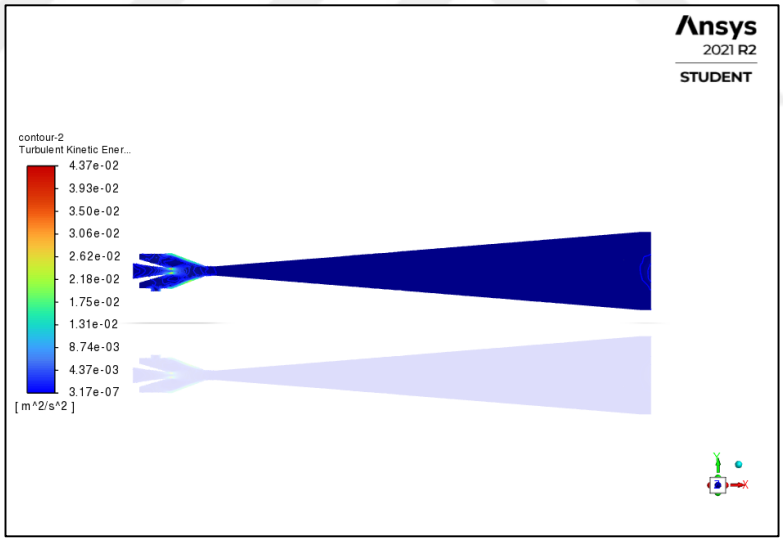

Figure 4.11 Turbulent Kinetic Energy Distribution at 364 K

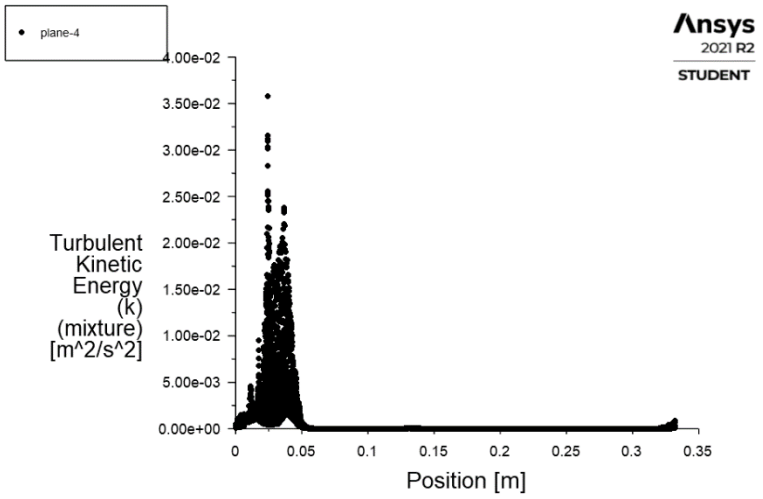

Figure 4.12 Turbulent Kinetic Energy Position Distribution at 364 K

4.4 Results for 369 K Inlet Temperature

Velocity distribution at 369 K inlet temperature is given in Figure 4.13. As seen from the Figure 4.14, maximum velocity occurs in the mixing chamber as 1,061276 m/s.

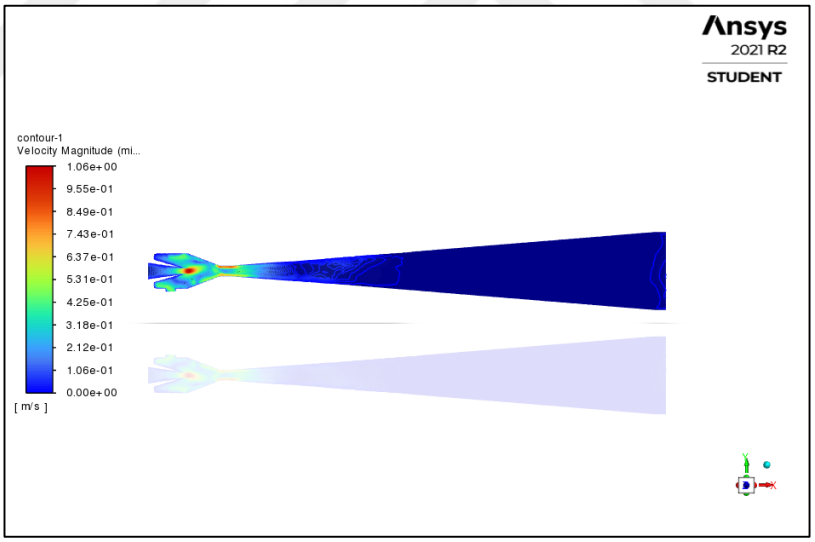

Figure 4.13 Velocity Distribution at 369 K

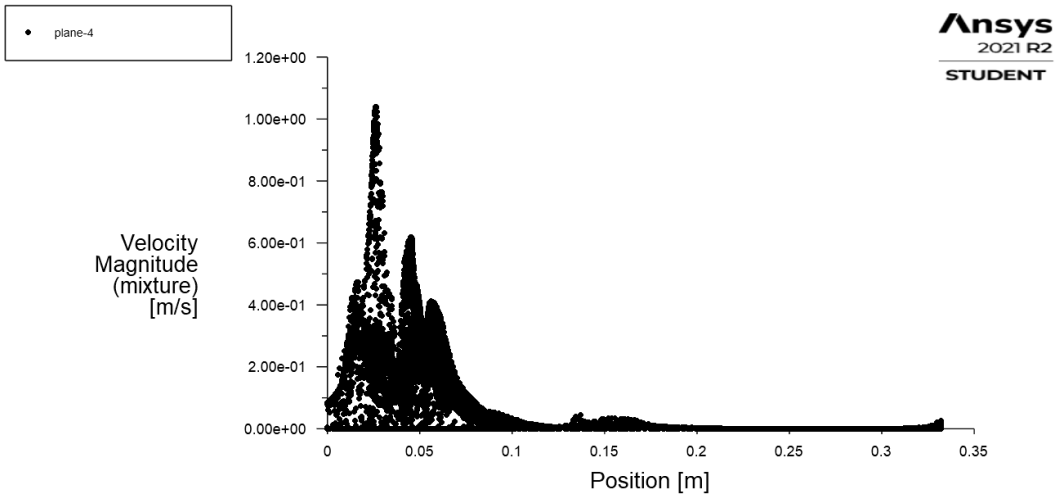

Figure 4.14 Velocity Position Distribution at 369 K

Turbulent kinetic energy of water ejector at 369 K inlet temperature is shown in Figure 4.15. Maximum value of the turbulent kinetic energy was found as $1.86 \cdot 10^{-1}$ J/kg as seen from the Figure 4.16.

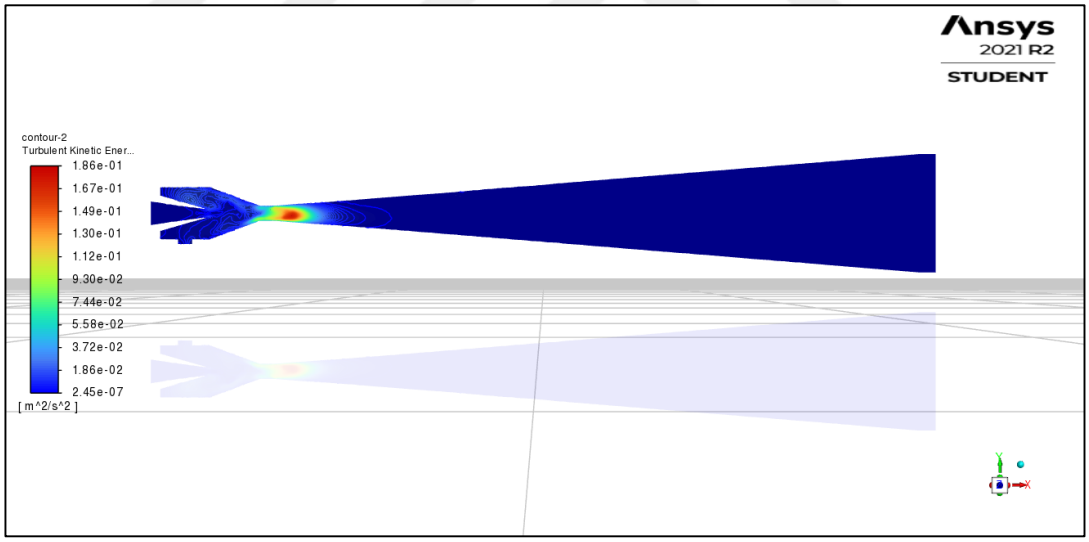

Figure 4.15 Turbulent Kinetic Energy Distribution at 369 K

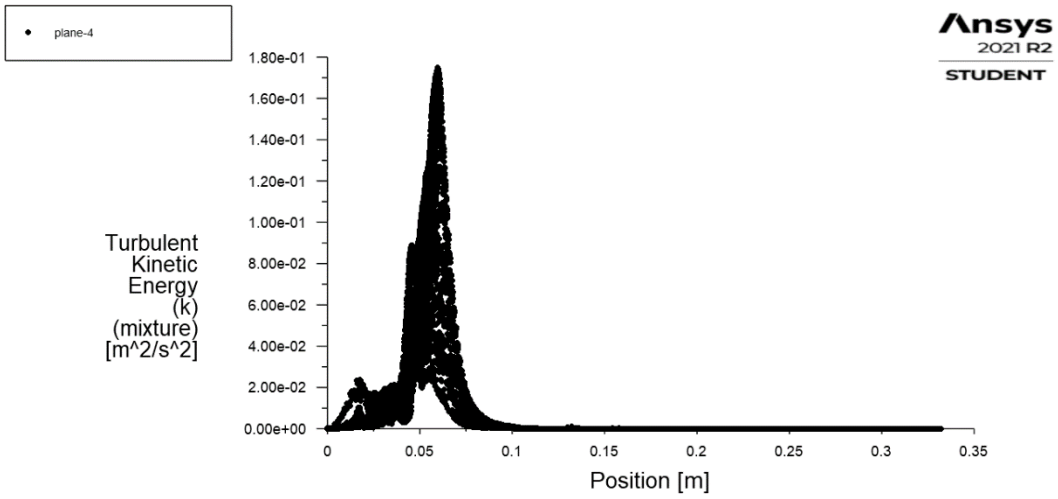

Figure 4.16 Turbulent Kinetic Energy Position Distribution at 369 K

4.5 Discussion of the Results

Viscosity means resistance to flow of fluid. When compared to a high viscous fluid, a fluid with low viscosity has a higher chance of becoming turbulent. Since 369 K has the lowest viscosity as seen from Table 3.4, it was expected to have higher turbulence kinetic energy in 369 K inlet temperature. This prediction is also consistent with the results of the analysis. It is also shown in Figure 4.17 that turbulence kinetic energy becomes greater with increasing temperature. For that reasons, analysis calculation time was doubled for 369 K inlet temperature in order to achieve better results and lower scale residues.

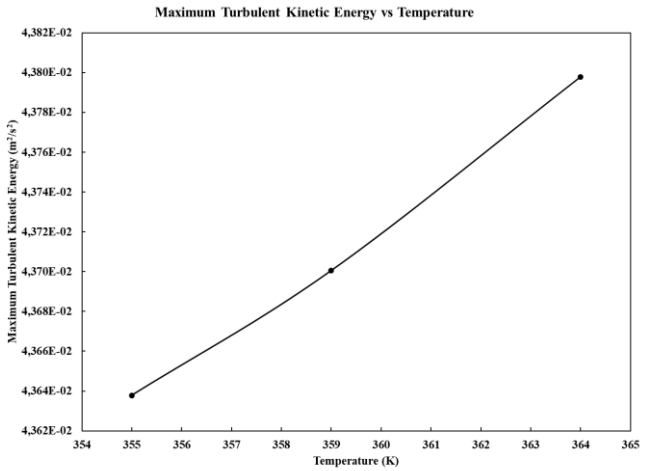

Figure 4.17 Comparison of Maximum Turbulent Energies between 355 & 364 K

From Table 3.2, maximum element volume is given as $2.067 \cdot 10^{-7}$ m^3. Average density of TNT is 1650 kg/ m^3. Thus, mass of the maximum sized element is found from equation below;

$$m_{max} = \rho_{TNT} \cdot V_{max} \tag{4.1}$$

as $m_{max} = 3.41 \cdot 10^{-4}$ kg.

By combining maximum of turbulent kinetic energy and mass of the maximum sized element, upper limit of the in-process energy can be found. Therefore; upper limit of the in-process energy for specified points were tabulated in Table 4.1 below.

Dabir et al. found sensitivity of the TNT as 30 J [44]. Moreover, study of Teipel shows that increasing water concentration decreases the sensitivity of the TNT-water emulsion [45]. Consequently, simulation findings show that selected parameter set provides safe operation according to literature.

Table 4.1 Maximum In-process Energies

Temperature (K)	In-Process Energy (J)	Safety Factor
354	$1.488 \cdot 10^{-5}$	$2.02 \cdot 10^{6}$
359	$1.490 \cdot 10^{-5}$	$2.01 \cdot 10^{6}$
364	$1.494 \cdot 10^{-5}$	$2.01 \cdot 10^{6}$
369	$6.347 \cdot 10^{-5}$	$4.73 \cdot 10^{5}$

CHAPTER 5

CONCLUSION

Requirement for the demilitarization increases rapidly because of the finite lifetime of the munitions. For a number of different reasons, including natural aging, becoming redundant prior to the advancement of newer technologies, becoming excess due to changed requirements, or being required to be destroyed due to international agreements; these munitions can reach the end of its useful life.

The objective of this study was to investigate different demilitarization techniques, evaluate their influence on the environment and determine their strengths and weaknesses. In terms of sustainable development, a product's material cycle should be converted to a "closed-loop economy" which means recycling of the material. Although recycling of some energetic materials such as NC and double base propellant are not feasible, most of the energetic materials can be recycled/reused with or without an additional treatment in line with an environmentalist approach. These recycled energetic materials can be used as commercial/military explosives or can be used as fertilizer due to high nitrogen content. Scrap metal of the munition casing can be reused as well. Even if the quality of the energetic material is not sufficient for recycling, energy released after destruction of these materials can be reclaimed. While using destruction technique, it is important to have a pollution abatement system to eliminate any pollutants and ensure the emission requirements. It will be essential to develop new greener energetic materials that have at least the same performance and level of insensitivity for the future [49].

When designing a disposal system, ensuring operational safety, knowing the material properties and determining safety-related criteria are essential. Since understanding the flow behavior of energetic material is critical for their safe usage, in-process rheology of the energetic material was analyzed by means of a CFD software. According to result of the simulation, system with selected parameters ensures necessary operational safety. Although hot water washout system is a proven technique and used widely in industry in a safe manner, the results of the analysis revealed and

emphasized the safety level of the technique. This study may provide a better insight when designing a disposal system considering environmental and safety concerns.

The study might be enhanced in the future by predicting possible operation areas with high turbulence intensity and applying necessary rheology analysis to ensure safe operation of energetic materials using the various techniques mentioned in this study. Additional studies can also be conducted on several types of energetic materials, such as RDX,HMX and so on.

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