Fire and Explosion Risk Assessment in a Combined Cycle Power Plant

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ABSTRACT: *Fire and explosion are the most prevalent accidents in chemical and process industries. Hence, identification of the hazard factors and the methods of controlling these two major accidents are very important in the process industries. In this study, fire and explosion hazards of some process units at a combined cycle power plant have been estimated using Dow fire and explosion index. The results of this study show that methane fueled turbine has the highest value of Dow index which is 321, turbine unit with gas oil and gas oil storage site have the Dow index values of 147.5 and 35.5 respectively. The loss control credit factor for methane fueled turbine unit was 0.36 and the Actual Maximum Probable Property Damage was 4.12 US million dollars. Maximum Probable Days Outage is estimated to be 50 days and finally, the loss due to unit pauses is calculated to be 3.03 US million dollars. In addition, the findings of the current study show that the gas oil storage unit suffers the highest amount of loss due to business interruption. The findings of the present study can be used for the improvement of inherent safety and can also be applied to estimate the losses due to fire and explosion.*

KEYWORDS: *Risk assessment, Fire, Explosion, Dow F&EI, Combined cycle power plant.*

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INTRODUCTION

Chemical and processing units are at risk of fire and explosion because of various reasons containing fire risks, chemical reactivity, and leakage of materials. These hazards are considered to be the first and second major hazards in chemical industries [1-4]. Moreover, releases of toxic materials are prevalent accidents in these industries. When the fire and explosion potential materializes, it can lead to human fatalities, serious injuries, loss of production, serious damages to properties, great financial losses and production interruption, job loss for the workers, and permanent damage to the environment [5, 6]. Therefore, identification of the hazard factors and the methods of controlling fire and explosion are very important in such industries [7, 8]. In this paper, the hazards of fire and explosion were estimated using one of the well-known hazard indices which is called Dow fire and explosion index. The Dow Fire and Explosion Index (hereafter called the Dow index) is a common hazard index [9]. Hazard indices using the numerical values classify the various sections of process industries in terms of fire and explosion and identify process areas with a high risk and also estimate the losses due to fire and explosion. However, in different sectors of the industry, quantitative risk assessments make the interpretation of results easier [10-12]. Dow Index is one of the quantitative risk analysis techniques which has been used by many researchers around the world. The researches done by *Gupta et al.* (1997), *Roy et al.* (2003), *Bernatik* and *Libisova* (2004), *Suardin et al.* (2007), and *Junjie et al.* (2019) are some of the examples [13-17]. These researches have indicated that this index has been applied for different objectives such as rating and classifying the hazard, indicating the economic effects and designing safe process industries. For instance, Suardin et al. (2005) came to the conclusion that by utilizing the Dow index, it is possible to design safer and more economical reactors and distillation systems. This index has been also applied to several studies in Iran, especially in the field of chemical industries [3]. For example, *Atrkar Roshan et al.* (2013) have applied Dow F&EI to estimate economic loss due to fire and explosion in petrochemical feed and product pipelines. In their research, Butadiene pipeline has ranked as high risk in which the hazard degree of fire and explosion was severe, radius of exposure of pipeline was 41.5 meter, damage factor was 0.87 and Actual Maximum Probable Property Damage and business interruption were 3.9 and 767 US million dollars, respectively [18]. *Jafari et al.* (2012), assessed the risk of fire and explosion in Iso-max unit of an oil refinery in Iran using Dow index and studied the influences of the controlling methods. The findings of Jafari's research showed that, 6 subunits out of 8 studied subunits had a severe fire and explosion risk. The separating container at high pressure was the most critical subunit of the Iso-max unit, holding an F&EI value of 220. The reactor feeding furnace was the least hazardous subunit with Dow Index value of 122 [19]. Also, *Ahmadi et al.* (2008 & 2012) in two studies have calculated the Dow index in selected process units of a petrochemical complex to determine the insurance premium. The results of *Ahmadi's* study has revealed that the stripper column with 226 F&EI value, actual maximum property damage of 6.7 US million dollars, 120 days of power outage, and business interruption loss of 89 US million dollars was identified as the most critical unit of the studied petrochemical complex. The least hazardous unit was the Naphtha storage tank with the F&EI value of 64 and actual maximum property damage of 0.36 US million dollars [20, 21].

Combined-Cycle Power Plant (CCPP)

A Combined-Cycle Power Plant (CCPP) uses gas and steam turbine together to generate up to 50 percent more electrical energy from the identical fuel compared to an old-style simple-cycle plant. The excessive heat from the gas turbine is moved to the adjacent steam turbine, which produces additional power [22]. Three main parts In CCPP are:

- *Gas turbine*

In Combined-cycle power plant the gas turbine engines generate power by mixing compressed air with high temperature fuel. The hot air-fuel combination moves through the gas turbine blades, making them spin. The fast-rotating turbine is connected to a generator that converts a portion of the rotating energy into electrical energy [23].

- *Heat recovery steam generator*

Heat Recovery Steam Generator (HRSG) uses the exhaust heat from the gas turbine in order to produce steam. This steam will be supplied to steam turbine later. Rest of the heat will be released through the exhaust stack [24].

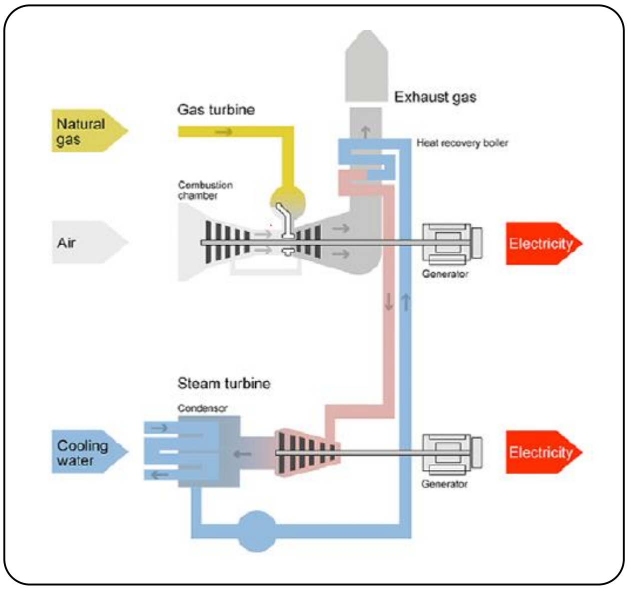

Fig. 1: Combined-cycle power plant diagram [26].

- Steam turbine

The steam turbine directs its energy to the generator drive shaft, in order to generate further electricity [25].

In the present study, fire and explosion hazards of some process units at a combined cycle power plant has been estimated using Dow index. The under study power plant uses of subcritical boilers and is comprised of process units and facilities such as gas units, vapor units and hydrocarbon storage site. Natural gas and gas oil are the main chemical materials that are used and stored in these facilities. These materials are consumed by turbine units as fuel to produce electricity.

EXPERIMENTAL SECTION

The fire and explosion risk analysis system evaluates the fire, explosion and reactivity potential of process equipment and its contents in an objective step-by-step method. The quantitative measurements which are applied in the analysis are in accordance with historical data, the latent energy of the material under study and the extent to which loss prevention practices are currently used [27]. Dow index which is a tool for plant engineers was developed by the Dow Chemical Company in the 1960s and the function of this index is to give relative value to the hazard of individual process unit losses because of fires and explosions and also to communicate the importance of related risks to management in terms which are easily understood [28].

Process unit selection

In the present study, the latest version of Dow fire and explosion index guideline published in 1994 was used to calculate the fire and explosion index at turbine processes and gas oil storage site of a thermal power plant. This method estimates the general risks of processing units through a simple and comprehensive way. Important factors for selecting suitable process units include: chemical energy potential, quantity of hazardous material, capital density, process's temperature and pressure, records of previous events that resulted in a fire and explosion accident, and units critical to plant operation. The general procedure of Dow index's calculation is shown in Fig. 2.

Process unit Hazards factor

The Dow index is calculated from Eq. 1:

$$\text{Dow Index} = MF \times F_1 \times F_2 = MF \times F_3 \quad (1)$$

Material Factor (MF)

Material factor is chemical potential energy released from the fire or explosion. It has a range of 1-40 and can be determined by considering the flammability and reactivity of the materials that exist at process unit [9, 27].

General process hazards factor (F1)

Some base factors such as exothermic reactions, endothermic processes, material handling and transfer, enclosed or indoor process units, accessibility, drainage and spill control in processing units could be considered in order to determine F_1.

Special process hazards (F2)

Special process hazards are 12 items that take a leading role in increasing the likelihood of a possible incident and include specific process conditions that generally help the main causes and result in fire and explosion accidents. They include toxic materials, pressure below the barometric pressure, operation at (or near to) the flammable limits, dust explosion, relief pressure, low temperature, flammable and unstable materials, corrosion and erosion, leakage induced by fittings and sealing washers, equipment with flames (burning equipment), hot oil heat exchangers, and

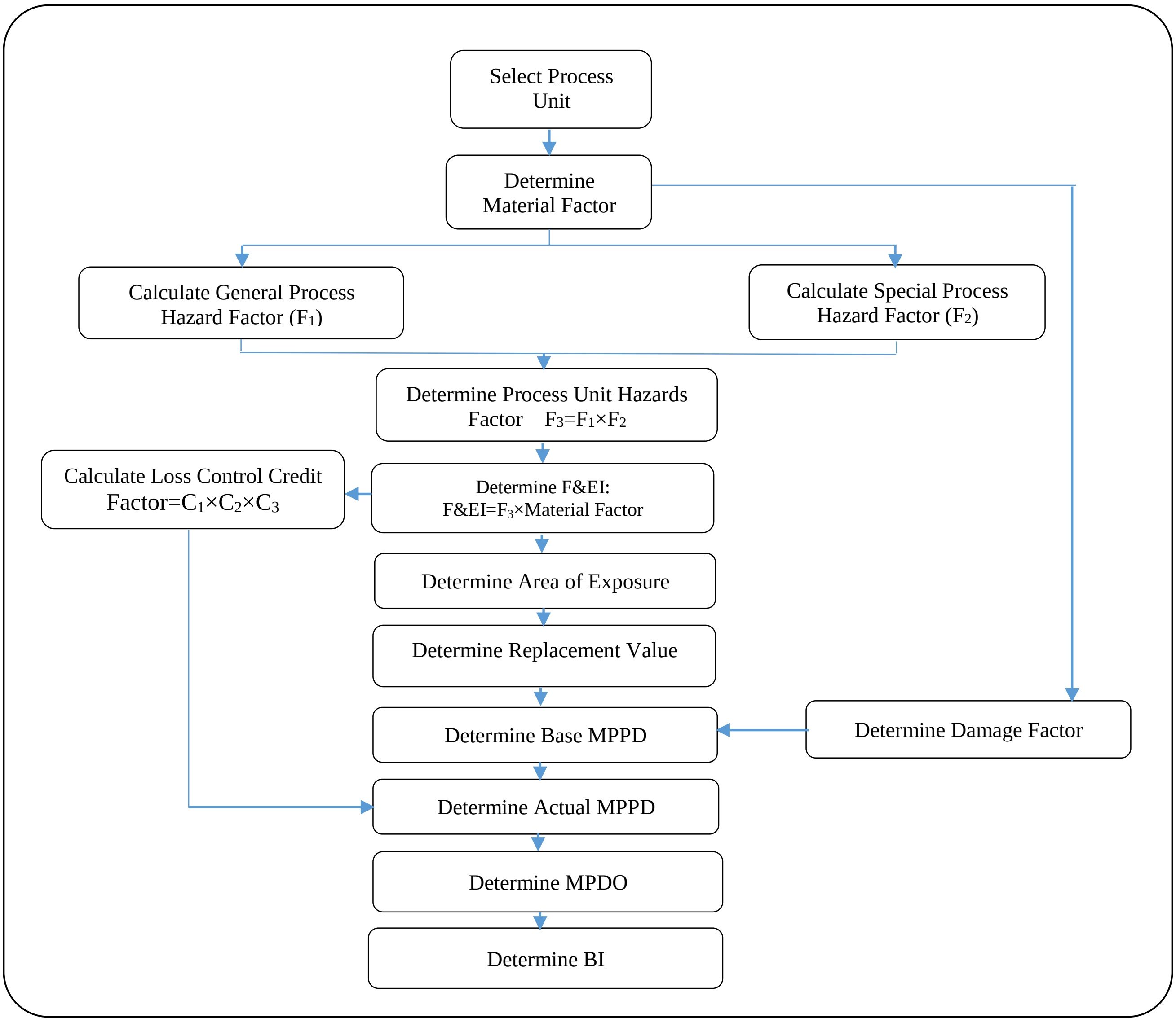

Fig. 2: Dow F&EI Procedure (Dow's Guideline, 1994)

rotating equipment. Each item is represented in terms of "penalties" and "credit factors" [19].

Process unit hazard factor (F3):

Process unit hazard factor is derived by multiplying the F_1 and F_2 values. Based on the value of the calculated index, the fire and explosion hazard of a pertinent process unit is ranked as light, moderate, intermediate, heavy or severe which are shown in Table 1 [27].

After the calculation of Dow index, the radius and area of exposure to fire and explosion incidents were determined by using Eq. (2) and (3):

$$\text{Radius of Exposure} = 0.84 \times \text{Dow index} \qquad (2)$$

$$\text{Area of Exposure} = \pi R^2 \qquad (3)$$

Where, R is the radius of exposure [27].

The value of the area is obtained from the replacement value of the property contained within it, including the inventory of material.

$$\text{Replacement value} = \text{Original Cost} \times 0.82 \times \text{EF} \qquad (4)$$

Where original cost is the capital cost, 0.82 is an allowance for items of cost not subject to loss or replacement, and EF is the escalation factor that is equal to inflation rate.

Table 1: Degrees of Hazard for Dow index -Dow's Guideline, 1994 [27].

Dow index Range	Degree of Hazard
1-60	Light
61-96	Moderate
97-127	Intermediate
128-158	Heavy
159-up	Severe

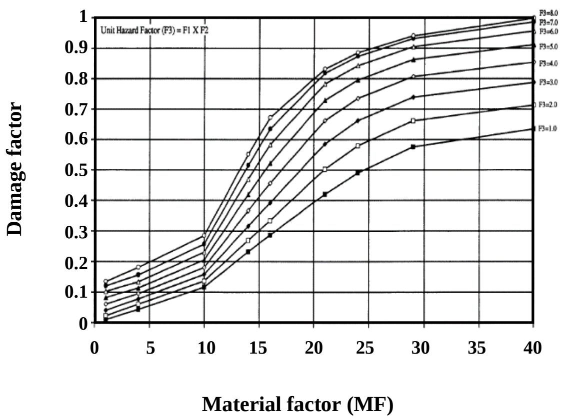

Fig. 3: Damage Factor Determination -Dow's Guideline, 1994 [27].

Loss control credit factors

The preventive and protective measures which have incorporation in the process design to decrease the fire and explosion hazard are considered in the form of Loss Control Credit Factors (LCCF). There are three classifications of loss control characteristics including: C_1(process control) which is derived from multiplying some factors such as emergency power, cooling system, explosion control, emergency shutdown, computer control, inert gas, operation instructions and procedures, reactive chemical review and other process hazard analyses. C_2 (material isolation) is comprised of remote control valves, dump / blow down, drainage and interlock items and finally C_3(fire protection) which accounts for leak detection (alarm and shutdown), fireproofing for structural steel, fire water supply, special systems, sprinkler systems, water curtains, foam, portable fire extinguishers / fire monitors and cable fire protection (instrumentation and electrical cables) [27-29]. Loss control credit factor is calculated using Eq. 5:

$$\text{LCCF} = C_1 \times C_2 \times C_3 \tag{5}$$

Loss Control features should be selected for the contribution they will actually make to reduce or to control the unit hazards which are being evaluated [27]. Similarly, by referring to Fig. 3 the Damage Factor is estimated using the Process Unit Hazards Factor (F_3) and the Material Factor (MF). Damage Factor shows the total effect of fire and explosion damage which are caused by a release of fuel or reactive energy from a Process Unit [27].

MPPD and BI calculations

The Base Maximum Probable Property Damage (Base MPPD) was obtained by multiplying the value of the area of exposure and damage factor [9]. The product of the Base MPPD and the Loss Control Credit Factor provided the Actual Maximum Probable Property Damage (Actual MPPD), which is shown in Eq. 6. The Actual MPPD was used to declare the maximum number of days necessary to reconstruct the plant to achieve its original capacity, i.e. the Maximum Probable Days' Outage (MPDO). MPDO is applied to estimate the financial loss caused by decline in production rate i.e. Business Interruption (BI) [29]. BI is the lost profit of the company due to fire and explosion incident and it is calculated by the eq. 7:

$$\text{Actual MPPD} = \text{Base MPPD} \times \text{loss control credit factor} \tag{6}$$

$$\text{BI}\ (\$\text{US}) = \frac{\text{mpdo}}{30} \times \text{VPM} \times 0.7 \tag{7}$$

Where VPM is the value of production per month.

RESULTS AND DISCUSSION

The results of Dow index calculations for units under study are illustrated in Table 2. Radius of exposure, area of exposure, value of area of exposure, damage factor, Base Maximum Probable Property Damage (MPPD), loss control credit factor, Actual MPPD, Days' Outage and BI loss have been calculated in US dollars for all of these units.

Methane fueled turbine unit

Methane, as a fuel in turbine unit with the material factor of 21 has the highest material factor among chemical materials that were presented in process units. Subsequently, based on the obtained results, this unit has allocated the highest value of Dow index to itself

Table 2: Results of Dow Fire and Explosion Index Calculation.

Process Unit	Turbine Unit	Turbine Unit	Storage Vessels
Major Material	Methane	Gas Oil	Gas Oil
Material Factor	21	10	10
Dow Index	321	147.5	35.5
Exposure Radius (m)	82.2	37.76	9
Area of Exposure (m^2)	21227	4480	254.5
Value of Area of Exposure ($MM)	13.8	2.91	13.32
Damage Factor	0.83	0.29	0.17
Base MPPD ($MM)	11.45	0.844	2.26
Loss Control Credit Factors	0.36	0.36	0.65
Actual MPPD ($MM)	4.12	0.304	1.47
Days' Outage (MPDO)	50	23	15
BI Loss ($MM)	3.03	1.4	4.96

Table 3: The Fire and Explosion Index Ranking of Units under Study.

Process Unit	Dow Index	Degree of Hazard for Dow Index				
		Light	Moderate	Intermediate	Heavy	Severe
Turbine Unit (Methane)	321					*
Turbine Unit (Gas Oil)	147.5				*	
Storage Vessels	35.5	*				

which is 321, therefore it can be understood that methane fueled turbine unit has the highest degree of fire and explosion risk as mentioned in Table 3 and consequently it is ranked as severe. Radius of exposure and area of exposure for this unit were calculated which are 82.2 m and 21227 m^2, respectively. Value of area of exposure was 13.8 US million dollars and the gained damage factor was 0.83 which means that in the event of fire and explosion incidents, more than 83% of equipment will be damaged. Base MPPD is derived by multiplying the value of area of exposure and damage factor which is 11.45 US million dollars. Loss control credit factor for this unit was 0.36 and by multiplying it to Base MPPD, Actual MPPD was 4.12 US million dollars. Maximum probable days' outage was 50 days and finally the loss due to unit pauses (BI) was 3.03 US million dollars.

Gas oil fueled turbine unit

When turbine unit uses gas oil as fuel, it has the second place in the risk ranking with Dow index value of 147.5 and it is categorized as heavy fire and explosion hazard in the plant under study.

Gas oil storage site

Gas oil storage site with Dow index value of 35.5 was the least hazardous one which is ranked as light fire and explosion hazard.

According to the results of this study, following results were obtained:

- It is indicated that turbine unit with methane as fuel is ranked at severe risk in terms of fire and explosion hazards. The main reason is the high material factor of the methane -with material factor 21-involved in the turbine unit process. For this reason, in order to further review the risks, consequence analysis was done for the jet fire of methane, with a volume of 5500 cubic meters and pressure of 367 psig, in the turbine unit for a leak scenario with hole diameter of 100 mm by PHAST software. Since the hazard domain of large leakage such as 100 mm scenario covers

Table 4: Thermal Radiation Intensity Limits (Marc J. Assael, and Konstantinos E. Kakosimos) **[32]**

Heat Flux ($kW \cdot m^{-2}$)	Effects on materials	Effects on humans
37.5	Equipment damage.	100% lethality in 1 in. 1% lethality in 10 s.
25	Minimum intensity for ignition of wood in prolonged exposure.	100% lethality in 1 min. Serious injuries in 10 s.
12.5	Minimum intensity for ignition, and melting of plastic tubes.	1% lethality in 1 min. 1st degree burns in 10 s.
4	-	No lethality. 2nd degree burns probable. Pain after exposure of 20 s.
1.6	-	Acceptable limit for prolonged exposure.

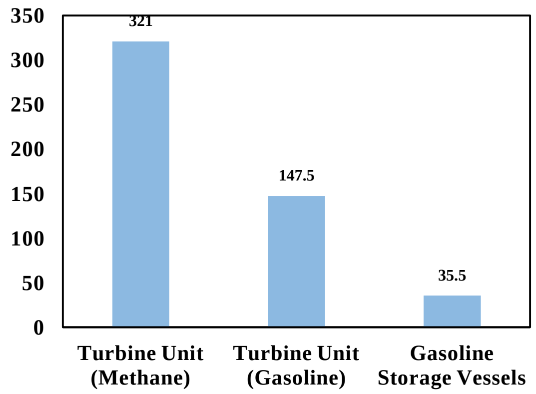

Fig. 4. Dow F&E index calculation at process units.

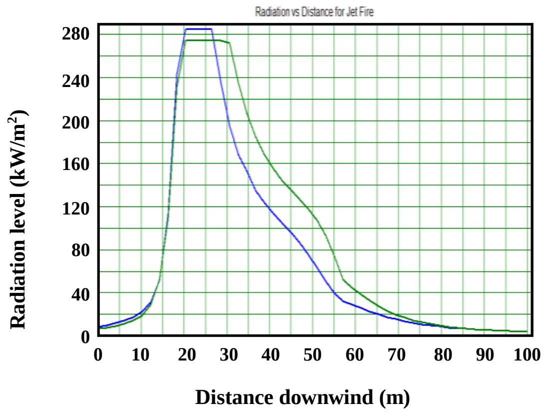

Fig. 5. Thermal radiation level of jet fire in different distances from methane storage in turbine unit.

small-leakage scenarios, in the present study, incidents with large leakage were considered as the selective scenario [30-31]. The results are shown in Fig. 5.

As shown in Fig. 5, the peak of thermal radiation occurs at distances less than 80 m from the methane storage in turbine unit. At distances more than 80 meters, due to the reduction of thermal radiation, no damage is done to the existing facilities. In a heat flux below 12.5 kW/m^2, there is not any special negative effect on materials (Table 4).

Therefore, appropriate control and protective measures should be established to reduce the fire and explosion risk in this unit.

- Another turbine unit with gas oil -with material factor of 10- as fuel is categorized as an item with heavy fire and explosion risk.

- Gas oil storage site is considered to be at the lowest risk of fire and explosion at the plant under study.

The findings of the current study have shown that gas oil storage unit constrains the highest amount of loss in money due to business interruption. The reason to this matter is related to the great amount of gas oil fuel which is stored in 4 vessels with the total capacity of 117-million-liters. Moreover, according to many researchers and their studies, reducing the volume of materials used in the process units which are flammable and reactive and frequently used in critical temperature and pressure, can cause a lower Dow fire and explosion index. Most of researchers such as *Etowa et al.* (2002) [11], *Suardin* (2005) [16] and *Suardin et al.* (2007) [33] and *Jafari et al.* (2012) [19] have agreed on this fact.

CONCLUSIONS

In the present study, the Dow index was calculated in process units of a combined cycle thermal power plant. Based on the results, methane fueled turbine unit with Dow index value of 321 has the highest degree of fire and explosion risk. Another turbine unit with gas oil fuel and Dow index value of 147.5 is ranked second with heavy fire and explosion risk. Finally, gas oil storage unit is recognized to have the least risk. Therefore, the methane fueled turbine unit is the most important unit in the combined cycle power plant in terms of fire and explosion hazards. On the other hand, the turbine unit with natural gas fuel has the highest hazard distance equal to 82.2 meters. So, it is necessary to consider this distance as a criterion in determining the safe distance in the unit. The value of equipment in the area of exposure of the turbine unit with natural gas fuel was estimated to be 13.8 US million dollars. Base Maximum Probable Property Damage (base MPPD) and the Actual Maximum Probable Property Damage (Actual MPPD) were estimated for this unit, which was calculated to be 11.45 and 4.4 US million dollars, respectively, and the maximum probable days outage (MPDO) of 50 days was calculated for this unit. Although the turbine unit with natural gas fuel is the most hazardous unit in many aspects, the turbine unit with gas oil fuel-despite the low amount of the fire and explosion index-has the highest amount of damage, which is estimated to be 4.96 US million dollars. This damage is caused by Business Interruption (BI) due to the large capacity of hydrocarbons (117-million-liters) stored in these tanks.

Therefore, by calculating Dow index in process units, one can estimate the economic and financial losses caused by fire and explosion in these units easily and even determine the radius of exposure affected by fire and explosion incidents. The results of this research can be used for optimization of the process unit to achieve inherently safer design. Moreover, the results can be applied as insurance premium.

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