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Abstract

Many emergency situations that arise in chemical, processing and transport industries are resulted from the emergency spill and ignition of flammable liquid. In this case, the spread of fire to neighboring objects represents a particular danger. Therefore, the elaboration of the fire-fighting measures requires taking into account the heat flow of the fire and as a result the information is needed on the shape and area of the spill. The model was constructed to determine the liquid spread dynamics and this model represents the system of differential equations. The first equation is of a parabolic type and it describes the liquid spread taking into consideration its consumption for infiltration, filling surface asperities and the burnout. Surface asperities are taken into consderation by the term equation that includes an average depth of asperities. To define the spill area we need to take into account the amount of the liquid required for the filling of those asperities during the liquid spill. The second equation is an ordinary differential equation and it describes the infiltration of liquid into the depth of the ground. Consideration was given to the instantaneous and continuous types of spill. The first type of spill occurs in the case of the catastrophic collapse of the liquid-containing tank and the second type is peculiar for the tank or pipeline damages. The finite difference method was used for the equation system solution. The developed algorithm enables the definition of the spill area, dynamics of its change and the liquid layer thickness.

Keywords (separated by '-'): Oil spill - Liquid infiltration - Spill fire

An Algorithm for Determining the Parameters of Oil Spill Fire

Oliinik Volodymyr

Abstract Many emergency situations that arise in chemical, processing and transport industries are resulted from the emergency spill and ignition of flammable liquid. In this case, the spread of fire to neighboring objects represents a particular danger. Therefore, the elaboration of the fire-fighting measures requires taking into account the heat flow of the fire and as a result the information is needed on the shape and area of the spill. The model was constructed to determine the liquid spread dynamics and this model represents the system of differential equations. The first equation is of a parabolic type and it describes the liquid spread taking into consideration its consumption for infiltration, filling surface asperities and the burnout. Surface asperities are taken into consderation by the term equation that includes an average depth of asperities. To define the spill area we need to take into account the amount of the liquid required for the filling of those asperities during the liquid spill. The second equation is an ordinary differential equation and it describes the infiltration of liquid into the depth of the ground. Consideration was given to the instantaneous and continuous types of spill. The first type of spill occurs in the case of the catastrophic collapse of the liquid-containing tank and the second type is peculiar for the tank or pipeline damages. The finite difference method was used for the equation system solution. The developed algorithm enables the definition of the spill area, dynamics of its change and the liquid layer thickness.

Keywords Oil spill · Liquid infiltration · Spill fire

1 Background

A considerable amount of extraordinary situations that arise during the storage and transportation of oil and petroleum products is originated from the emergency spill of liquid [1]. On the one hand, the infiltration of liquid into the ground reduces

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the liquid layer thickness on the ground surface, i.e. the spread area. On the other hand, it results in the pollution of soil, the underground [2] and ground waters [3]. However, the ignition of liquid is the main danger and it threats with the spread of fire to neighboring technological objects and natural landscapes [4]. For example, the fire at the oil terminal in Havana (Cuba, 2022) was caused by the hit of lightning right to the tank and it resulted in the collapse and ignition of the three oil tanks with the capacity of 50,000 m^3 each. In Texas (the USA, 2021) a train with oil products derailed and collided with the truck. Three tanks ignited and the flame height attained several tens of meters. Such large-scale fires result in the emission of harmful substances into atmosphere [5]. Spreading to large distances, these have an undesirable effect on the state of air and create certain risks for the population [6].

To develop the emergency situation liquidation and localization plans due to the emergency spill of the flammable liquid and to select appropriate extinguishing agents [7] the firemen need the information on the size of spill and the shape of it and on the dynamics of its change. Paper [8] studies a large-scale fire caused by the liquid spill in the railway tunnel. A specific feature of the approach is the division of the tunnel space into individual zones and the derivation of the temperature distribution therein. In this case, the oil spill area is considered to be a constant value and it is preset apriori. Paper [9] describes the construction of the model of ascending flows formed over the flammable liquid spill; however no consideration is given to the spill formation dynamics. Paper [10] gives consideration to the thermal effect of the fire onto steel structures, but no consideration is given to the fire area change dynamics. Ecological characteristics of the extinguishing agents used for the fighting of the fires caused by spilled oil products were analyzed in [11]. However, it gives no consideration to the spill formation process and the effect of the liquid infiltration into the ground on the fire parameters.

Paper [12] describes the construction of the model of the thermal effect of the fire caused by the spilled flammable liquid on the petroleum tank, but the spill shape and area are assumed to be constant. Paper [13] is devoted to experimental investigations of the spread of n-butanol with a simultaneous fire spread. The drawback of this approach is the dependence of the obtained data on experimental conditions and impossibility of their generalization. Paper [14] studies the spread and burnout of flammable liquids on the fire-resistant glass surface. However, this model fails to take into account the surface asperities that are inherent to the real ground and the infiltration of the liquid into the ground. One of the approaches to the simulation of the liquid spread on the horizontal surface is based on the principle of the gravitational spread of the cylindrical layer of liquid [15]. It consists in the analysis of gravitation forces, the surface tension and friction that are specific for the spread process. However, the spread surface hydrodynamics is out of focus in this case. Paper [16] analyzes the models of the liquid spread on the solid surface. It suggests the model updating based on the comparison of the calculation data obtained using the model [17] and experimental data. The drawback of this approach is that the calculated correction is defined by the conditions of the carried out experimental investigations and as a consequence it is impossible to generalize the obtained data. The model of the liquid infiltration into the ground was constructed in [18]. In [19], the authors suggest the method for the determination of the parameters of the liquid infiltration into the ground, in particular hydraulic conductivity coefficient, ground porosity factor and the suction head. The method is based on the solution of the problem of the minimization of the difference in calculated and experimental data.

The analysis of the models constructed for the spread of flammable liquids showed that these fail to take into account the surface asperities. In its turn, it results in the spill size estimation errors and also in the errors of the estimation of the dynamics of its formation.

The purpose of this research was to construct the algorithm for the determination of the spread parameters of the flammable liquid on the ground.

2 Determining the Parameters of Oil Spill Fire

2.1 Mathematical Model

The spread of the liquid on the sloped surface with the simultaneous infiltration of it into the ground is described by the system of differential equations [16]

$$\frac{\partial h}{\partial t} = R\left[\frac{\partial}{\partial x}\left[h^3\left(\frac{\partial h}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[h^3\left(\frac{\partial h}{\partial y}\right)\right] - \gamma\frac{\partial}{\partial x}h^3\right] - \varphi\, K\frac{h+z+h_f}{z}; \tag{1}$$

$$\frac{\partial z}{\partial t} = K\frac{h+z+h_f}{z}, \tag{2}$$

where R is an effective diffusion coefficient:

$$R = \frac{\rho g}{3\mu}\cos\theta = \frac{g}{3\nu}\cos\theta;$$

$\gamma = \text{tg}\theta$; θ is the surface inclination angle; $h(x, y)$ is the liquid head at the point (x, y); μ, ν are dynamic and kinematic liquid viscosities; ρ is the liquid density; g is the free fall acceleration; $z(x, y)$ is the depth of infiltration at the spill point (x, y); K is the hydraulic conductivity of the soil; ϕ is the soil porosity; h_f is the suction head.

In addition to the porosity the real surface has the asperities caused by the cracks, hollows, etc. Therefore, the liquid spread is accompanied by the filling of such surface irregularities. It means that a certain volume of the liquid is spent for the filling of available hollows or recesses

$$V_{dp}(t) = S(t)h_{dp},$$

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where $V_{dp}(t)$ is the volume of liquid that filled the recesses at the moment of time t; $S(t)$ is the spill area at the moment of time t; h_{dp} is the average depth of surface asperities. The liquid burnout results in a decrease of the thickness of its layer by the value of

$$\Delta_{burn} = \frac{\eta}{\rho} 1_{\Omega_b}(x, y),$$

where η is the specific rate of the liquid burnout; ρ is its density; $\Omega_b(t)$ is the burning liquid area at the moment of time t;

$$1_{\Omega_\mathbf{b}}(x, y) = \begin{cases} 1, & (\mathbf{x}, \mathbf{y}) \in \Omega_\mathbf{b}, \\ 0, & (\mathbf{x}, \mathbf{y}) \notin \Omega_\mathbf{b}. \end{cases}$$

Hence, taking into consideration the amount of liquid spent to fill surface asperities and for the burnout, the liquid spread equation system will be expressed as

$$\frac{\partial h}{\partial t} = R\left[\frac{\partial}{\partial x}\left[\tilde{h}^3\left(\frac{\partial \tilde{h}}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\tilde{h}^3\left(\frac{\partial \tilde{h}}{\partial y}\right)\right] - \gamma \frac{\partial}{\partial x}\tilde{h}^3\right] - \varphi\, K \frac{h + z + h_f}{z} - \frac{\eta}{\rho} 1_{\Omega_b}(t); \quad (3)$$

$$\tilde{h} = \begin{cases} h - h_{dp}, & h - h_{dp} > 0; \\ 0, & h - h_{dp} \le 0; \end{cases} \quad (4)$$

$$\frac{\partial z}{\partial t} = K \frac{h + z + h_f}{z}. \quad (5)$$

In the case of the instantaneous spill of a volume V at the moment of time $t = 0$ at the point (0,0), the system (3)–(5) is supplemented by the initial condition

$$h(x, y, 0) = V\delta(x)\delta(y); \quad z(x, y, 0) = 0, \quad (6)$$

where $\delta(x)$ is the delta-function. For the continuous flow of liquid the system of equations for the liquid spread and infiltration is expressed as

$$\frac{\partial h}{\partial t} = R\left[\frac{\partial}{\partial x}\left[\tilde{h}^3\left(\frac{\partial \tilde{h}}{\partial x}\right)\right] + \frac{\partial}{\partial y}\left[\tilde{h}^3\left(\frac{\partial \tilde{h}}{\partial y}\right)\right] - \gamma \frac{\partial}{\partial x}\tilde{h}^3\right] - \varphi\, K \frac{h + z + h_f}{z} + \frac{\eta}{\rho} 1_{\Omega_b}(t) + v(t)\delta(x - x_0)\delta(y - y_0); \quad (7)$$

$$\tilde{h} = \begin{cases} h - h_{dp}, & h - h_{dp} > 0; \\ 0, & h - h_{dp} \le 0; \end{cases} \quad (8)$$

$$\frac{\partial z}{\partial t} = K\frac{h + z + h_f}{z}; \tag{9}$$

with a zero initial condition

$$h(x, y, 0) = 0, \quad z(x, y, 0) = 0, \tag{10}$$

where v(t) is the volumetric velocity of the liquid flow (m^3/s); (x_0, y_0) is the coordinate of the point of the liquid outflow.

If the liquid outflow faces certain obstacles that prevent the liquid spread (for example railway embankments), then the spread occurs in some domain of Φ (finite or infinite). In this case, at the boundary of $\partial\Phi$ of the Φ domain the edge condition of

$$\left.\frac{\partial h}{\partial n}\right|_{\partial\Phi} = 0 \tag{11}$$

will be specified. ∂/∂n is a derivative in the direction of the normal up to the domain boundary.

2.2 Numerical Simulation

For the hands-on use of the obtained models we need to solve equation systems (3)–(5) and (7)–(9) with appropriate initial and edge conditions. The derivation of the analytical solution is impossible due to the nonlinearity of equations for liquid layer thickness and the infiltration depth. Let's construct a regular 2D mesh with the pitch Δx in the directions of X and Y in the plane of the spill. The time axis pitch will be Δt.

For the transition to the regular mesh we will approximate the δ-function using the finite function in the form of the pyramid of a height H. The pyramid height H is chosen so that its volume is equal to

$$V = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \delta(x - x_0)\delta(y - y_0)dxdy = 1. \tag{12}$$

Then

$$H = \frac{3}{\Delta x^2}.$$

For the mesh nodes (x_i, y_j) derivatives can be expressed as

$$\frac{\partial \tilde{h}}{\partial t} \approx \frac{\tilde{h}(x_i, y_j, t_{m+1}) - \tilde{h}(x_i, y_j, t_m)}{\Delta t}. \tag{13}$$

$$\frac{\partial}{\partial x} f(x_i, y_j) \approx \frac{1}{\Delta x}\left(f_{i+\frac{1}{2}\,j} - f_{i-\frac{1}{2}\,j}\right); \tag{14}$$

$$\frac{\partial}{\partial y} f(x_i, y_j) \approx \frac{1}{\Delta x}\left(f_{i\,j+\frac{1}{2}} - f_{i\,j-\frac{1}{2}}\right), \tag{15}$$

where

$$f_{i+\frac{1}{2}\,j} = \frac{f(x_i, y_j) + f(x_{i+1}, y_j)}{2}; \quad f_{i-\frac{1}{2}\,j} = \frac{f(x_{i-1}, y_j) + f(x_i, y_j)}{2};$$

$$f_{i\,j+\frac{1}{2}} = \frac{f(x_i, y_j) + f(x_i, y_{j+1})}{2}; \quad f_{i\,j-\frac{1}{2}} = \frac{f(x_i, y_{j-1}) + f(x_i, y_j)}{2}.$$

Then the derivatives in (3) or (7) can be substituted by approximated expressions

$$\frac{\partial}{\partial x}\left[\tilde{h}^3\left(\frac{\partial \tilde{h}}{\partial x}\right)\right] \approx \Delta_{ij}^{xx} = \frac{1}{\Delta x}\left[\tilde{h}^3_{i+\frac{1}{2}\,j}\left(\frac{\partial \tilde{h}}{\partial x}\right)_{i+\frac{1}{2}\,j} - \tilde{h}^3_{i-\frac{1}{2}\,j}\left(\frac{\partial \tilde{h}}{\partial x}\right)_{i-\frac{1}{2}\,j}\right]$$

$$= \frac{1}{(\Delta x)^2}\left[\left(\frac{\tilde{h}_{ij} + \tilde{h}_{i+1\,j}}{2}\right)^3\left(\tilde{h}_{i+1\,j} - \tilde{h}_{ij}\right) - \left(\frac{\tilde{h}_{ij} + \tilde{h}_{i-1\,j}}{2}\right)^3\left(\tilde{h}_{ij} - \tilde{h}_{i-1\,j}\right)\right]; \tag{16}$$

$$\frac{\partial}{\partial y}\left[\tilde{h}^3\left(\frac{\partial \tilde{h}}{\partial y}\right)\right] \approx \Delta_{ij}^{yy} = \frac{1}{\Delta x}\left[\tilde{h}^3_{i\,j+\frac{1}{2}}\left(\frac{\partial \tilde{h}}{\partial y}\right)_{i\,j+\frac{1}{2}} - \tilde{h}^3_{i\,j-\frac{1}{2}}\left(\frac{\partial \tilde{h}}{\partial y}\right)_{i\,j-\frac{1}{2}}\right]$$

$$= \frac{1}{(\Delta x)^2}\left[\left(\frac{\tilde{h}_{ij} + \tilde{h}_{i\,j+1}}{2}\right)^3\left(\tilde{h}_{i\,j+1} - \tilde{h}_{ij}\right) - \left(\frac{\tilde{h}_{ij} + \tilde{h}_{i\,j-1}}{2}\right)^3\left(\tilde{h}_{ij} - \tilde{h}_{i\,j-1}\right)\right]; \tag{17}$$

$$\frac{\partial}{\partial x}\left(\tilde{h}^3\right) \approx \Delta_{ij}^{x} = \frac{1}{\Delta x}\left[\tilde{h}^3_{i+\frac{1}{2}\,j} - \tilde{h}^3_{i-\frac{1}{2}\,j}\right]$$

$$= \frac{1}{\Delta x}\left[\left(\frac{\tilde{h}_{ij} + \tilde{h}_{i\,j+1}}{2}\right)^3 - \left(\frac{\tilde{h}_{ij} + \tilde{h}_{i\,j-1}}{2}\right)^3\right]. \tag{18}$$

The right side of the infiltration Eq. (9) acquires infinite values at $z = 0$. Therefore, we will use the implicit scheme for it for this equation and after the transformation we get

$$z_{ij}(t_{k+1}) = \frac{1}{2}\left[z_{ij}(t_k) + K\Delta t + \sqrt{\left(z_{ij}(t_k) + K\Delta t\right)^2 + 4\left(h_{ij} + h_f\right)K\Delta t}\right]. \tag{19}$$

Taking into consideration the expressions (13)–(19), the differential equations for the liquid spread, burnout and infiltration (3)–(5) in the case of the instantaneous spill will be expressed as

$$h_{ij}^{k+1} = h_{ij}^k + R\left[\Delta_{ij}^{xx} + \Delta_{ij}^{yy} - \gamma\Delta_{ij}^{x}\right]\Delta t - \varphi\, K\frac{h_{ij}^k + z_{ij}^{k+1} + h_f}{z_{ij}^{k+1}}\Delta t - \frac{\eta}{\rho}1_{\Omega_b}(t_k)\Delta t \tag{20}$$

$$\tilde{h}_{ij}^k = \begin{cases} h_{ij}^k - h_{dp},\ h_{ij}^k - h_{dp} > 0; \\ 0,\ h_{ij}^k - h_{dp} \le 0; \end{cases} \tag{21}$$

$$z_{ij}^{k+1} = \frac{1}{2}\left[z_{ij}^k + K\Delta t + \sqrt{\left(z_{ij}^k + K\Delta t\right)^2 + 4\left(h_{ij}^k + h_f\right)K\Delta t}\right]; \tag{22}$$

$$h_{ij}^k = h\left(x_i, y_j, t_k\right); \quad \tilde{h}_{ij}^k = \tilde{h}\left(x_i, y_j, t_k\right); \quad z_{ij}^k = z\left(x_i, y_j, t_k\right).$$

In the case of the continuous flow of liquid the Eq. (20) should be replaced by

$$h_{ij}^{k+1} = h_{ij}^k + R\left[\Delta_{ij}^{xx} + \Delta_{ij}^{yy} - \gamma\Delta_{ij}^{x}\right]\Delta t - \varphi\, K\frac{h_{ij}^k + z_{ij}^{k+1} + h_f}{z_{ij}^{k+1}}\Delta t$$
$$- \frac{\eta}{\rho}1_{\Omega_b}(t_k)\Delta t + \frac{3v(t_k)}{\Delta x^2}1_{ij}\Delta t \tag{23}$$

where

$$1_{ij} = \begin{cases} 1,\ \left(x_i, y_j\right) = (0,\ 0); \\ 0,\ \left(x_i, y_j\right) \ne (0,\ 0). \end{cases}$$

In the case of the instantaneous spill initial conditions (6) will be expressed as

$$h_{ij}^0 = \frac{3V}{\Delta x^2}1_{ij};\ z_{ij}^0 = 0. \tag{24}$$

For the continuous liquid outflow process initial conditions (10) are transformed to

$$h_{ij}^0 = 0; \quad z_{ij}^0 = 0. \tag{25}$$

When switching over to finite differences the impermeability condition (11) is transformed in the following way. If an obstacle is available at a point A neighboring with the point (x_i, y_j), then to calculate the Δ_x, Δ_{xx}, Δ_y, Δ_{yy} values using the formulas (14)–(17) we will assume that

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$$\tilde{h}_A^k = \tilde{h}_{ij}^k. \qquad (26)$$

The condition (26) ensures that the derivative in the direction of an obstacle is equal to zero.

3 Results

Figure 1 gives as an example the simulation data obtained for the spilled diesel fuel on the ground surface with the angle of inclination $\theta = 3°$ and the fuel outflow intensity of $v(t) = 2$ l/s. Kinematic viscosity $\nu = 4.5$ mm^2/s; density $\rho = 830$ kg/m^3; specific mass burnout rate of $\eta = 0.055$ kg/(m^{2}s). Ground infiltration parameters are: $K = 1.68{\cdot}10^{-7}$ m/s; $h_f = 0.95$ m; $\phi = 0.31$.An average depth of the ground asperities is $h_{dp} = 1.7$ cm. The coordinate system was selected so that its origin coincides with the liquid outflow point and the X-axis coincides with the downward surface inclination direction. The simulation of the liquid spread, infiltration and burnout was carried out with the spatial coordinate pitch of $\Delta x = 0.2$ m and the time axis pitch of $\Delta t = 0.01$ s.

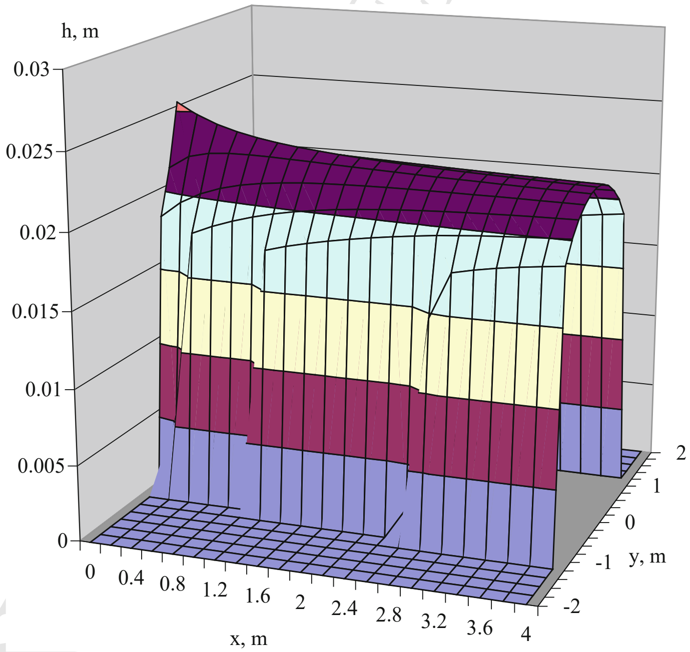

Fig. 1 The layer thickness for the liquid spilled on the sloped surface

The simulation shows that the liquid layer thickness distribution over time is heading towards a stable distribution. It should be noted that the stable distribution for specified conditions (see Fig. 1) was established after 120 s.

4 Discussion

The liquid spread and burnout model (3)–(5) relies on the liquid spread model for the sloped surface (1) and the Green-Ampt model that describes the infiltration of liquid into the ground (2). The amount of liquid spent to fill surface asperities and for the burnout was taken into account additionally.

Initial conditions are defined by the liquid spread type, i.e. instantaneous or continuous. The instantaneous spill occurs in the case of the catastrophic collapse of the tank. In this case, initial conditions are expressed as (6). The continuous spread occurs in the case of the tank or pipeline damage and it results in the gradual increase of the volume of the spilled liquid. In this case, the differential equation of the liquid spread (7) is added with the term that includes the δ-function. Liquid spread obstacles are described by the edge conditions that correspond to the impermeability of liquid through the spread domain boundary (11).

For solving the Eqs. (3)–(5) and (7)–(9) the method of finite differences is used. A regular mesh with the pitch of Δx was constructed on the liquid spread plane. The approximation of the derivative by the expressions (13)–(18) enables the transition to the equation of finite differences (20) or to the Eq. (23) that describes the liquid spread, infiltration and burnout for instantaneous and continuous outflows. The use of implicit difference scheme for the infiltration equation gives the expression for finite differences (22).

The algorithm used for determining the parameters of the spilled liquid is executed in the rectangular domain in which the simulation is done with the preset spatial axes pitch and time axis pitch. Afterwards, cyclic calculations were done using the formulas (20)–(23). The execution of the algorithm is terminated as soon as the liquid layer thickness reaches a stable distribution. The use of the algorithm enables the definition of the spread area, the dynamics of its change and the liquid layer thickness.

The enlargement of the average depth of surface asperities results in the reduction of the spill area due to the need for the filling of those asperities by the liquid. The liquid spread area is defined not only by the volume of the spilled liquid but also by the volumetric rate of its outflow. As the outflow is decelerated the portion of liquid that infiltrates into the depth of ground is increased.

The obtained data can be used for the calculation of the thermal effect of fire on neighboring technological objects. The results can also be used for the designing of the fire alarm systems [20].

5 Conclusions

The system of differential equations that describe the liquid spread on the sloped surface, the depth infiltration and the liquid burnout has been constructed. In addition, the availability of the surface asperities that should be filled by the spilled liquid was also taken into account. The spread type, i.e. instantaneous or continuous was taken into account in initial conditions. The method of finite elements was used for the solution of the equation system.

The developed algorithm enables the definition of the spread area, the dynamics of its change and the liquid layer thickness.

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Chapter 43

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