

1 Experimental study on the spread and burning behaviors of continuously
2 discharge spill fires under different slopes

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11
12 **Abstract:** This paper examines the effects of the slope on the burning and spread
13 process of JP-4 continuous spill fires. Spill fires experiments were conducted on
14 surfaces with different slope angles ($0^{\circ}\sim 3^{\circ}$) in a rectangular trench ($0.8\text{m}\times 6\text{m}$). The
15 spread and burning behaviors including the spread process, burning rate and flame
16 height are recorded and analyzed. The results indicate that the whole spread process
17 can be divided, based on the burning area variations with time, into four phases: 1)
18 burning layer spread, 2) shrink process, 3) steady burning, and 4) extinguishment. The
19 results also show that a large slope can increase the spread rate and as a result shorten
20 the duration of the burning layer spread and shrink process pphases. In addition, it is
21 found that the slope has a more significant effect on the maximum spread area than the
22 steady burning area. The steady burning rate decreases with increasing slope and the
23 ratio of the steady burning rate of a spill fire and that of the corresponding pool fire is
24 nearly constant. The flame height of continuous spill fires is also well predicted by an
25 empirical model with a dimensionless heat release rate and equivalent pool diameter.
26 The experimental data presented in the work will provide a basis for further studies of
27 liquid fuel spill fire on an inclined surface.

28 **Key words:** continuous spill fires, slope angle, spread process, burning rate, flame
29 height

Nomenclature		w	Thickness decrease per time
a	Absorbed coefficient, m^{-1}	Greek symbols	
c	Specific heat capacity, $J/(kg \cdot K)$	σ	Surface tension, N/m
H_c	Heat of combustion, kJ/kg	β	Absorption extinction coefficient
h	Thickness of fuel, m	ρ	Density, kg/m^3
k	A constant	θ	Contact angle
L	Length of spread, m	Subscripts	
Q	Discharge rate, L/s	t	Real time
\dot{Q}	Heat release rate, kW	min	Minimum value
q	Heat flux, kW/m^2	steady	Steady burning
S	Burning area, m^2	rad	Heat radiation
T	Temperature, K	cov	Heat convection
W	Width of trench, m	cod	Heat conduction

31

32 **1. Introduction**

33 One of major hazards of liquid fuels during their transportation, processing and
34 storage is that they can be relatively easily involved in leakage which will then be turned
35 into continuous spill fires after ignition in the presence of an ignition source such as
36 sparks [1, 2]. For continuous spill fires, as the spreading area is not confined completely
37 by horizontal physical boundaries, most liquid burning fuels will spread in downhill
38 direction [3,4]. In the development of spill fire accidents, the spreading process is
39 usually followed by high flame temperatures and large radiative heat fluxes to adjacent
40 objects, thus posing a huge threat to nearby facilities and further triggering accident
41 escalation, which is commonly known as the domino accident [5]. This was
42 demonstrated in a serious spill fire accident that occurred in April 6, 2015 at Gulei of
43 Fujian Province (a Chinese city). It was reported that the liquid fuel from a pipe leakage
44 was ignited and then flowed to a low terrain place leading to three adjacent storage
45 tanks collapsing and more than ten persons injured [6]. In actual accidents, the
46 development of continuous spill fires is closely related to the ground slope which
47 directly determines the spread and burning process. Moreover, the development of spill
48 fire accidents also determines the proper firefighting time and corresponding measures.
49 Therefore, it is meaningful to investigate the development of spill fires and analyze the
50 detail spread process, particular for the spread on slope surface.

51 In the last decades, liquid fuel spread and pool fire burning have attracted significant
52 interest among researchers [7-10]. These studies were focused on either liquid layer
53 spread without ignition or burning rate with a fixed boundary. However, in most fire
54 accidents involving liquid fuels, the fuels tend to spread while burning, particularly for
55 the liquid fuel transportation process [3,4]. To date, the research on continuous spill
56 fires is relatively limited, particular for the continuous experiments. Gottuk et al. [3]
57 conducted continuous spill fire experiments on a concrete surface using JP-5 and JP-8,
58 and they found that the mass burning rate of continuous spill fires is around 20% than
59 that of pool fires with the same surface area. Benfer [11] performed a series of
60 systematical spill fire experiments using different substrates and fuels [11] and found
61 that the properties of both the substrate and fuel contribute to the lower burning rate
62 and subsequently introduced a coefficient to account for the burning rate for
63 instantaneous spill fires [11]. The spread behaviors of continuous spill fires were
64 examined in [12,13] by performing continuous spill fire experiments on water surface
65 in a rectangular trench (1m × 12m) and the whole spread process can clearly be
66 characterized by different phases.

67 The aforementioned studies on spill fires were all performed on a flat surface.
68 However, the spread on inclined surface are one of the most common scenarios in real
69 spill fire accidents [14,15]. Ingason investigated the continuous gasoline burning rate
70 on the concrete surface and observed that the averaged heat release rate decreases with
71 the increase of slope [15]. Li et al. studied experimentally the continuously released n-
72 heptane spill fire in a steel trench (3×0.15 m), with five different slopes [16], in which
73 five phases of spill fire were divided and characterized according to the real time
74 burning area variations. However, as the width of the trench is relatively small, the
75 burning rate is controlled mainly by convection, which would be very different from
76 the real fire accident scenarios, in which radiation will be the dominating factor.
77 Moreover, the fuel spread on the concrete surface or the iron surface cannot be
78 controlled well and therefore the real burning area cannot be measured accurately.
79 Clearly, the effects of the slope on the spread and burning behaviors of continuous spill
80 fires, especially on the inclined surface, are still little known and should be further

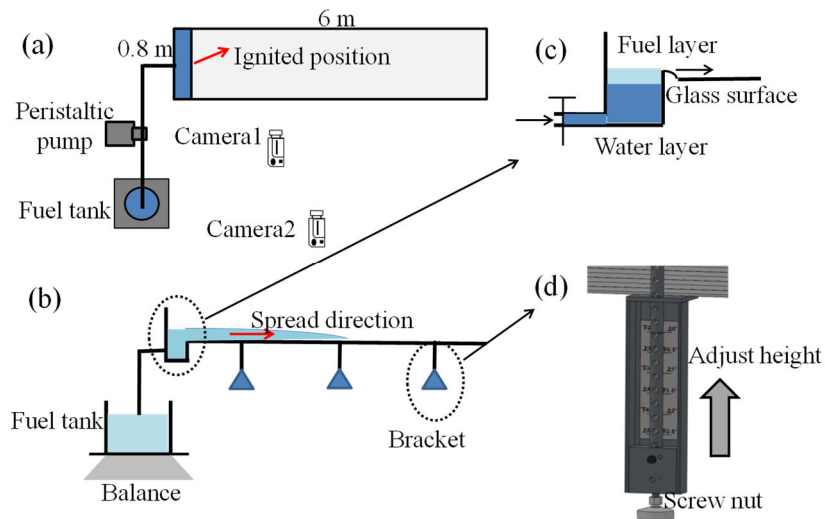
81 studied as noted by several researchers [3,4,13-17].

82 To fill this knowledge gap, this work aims to examine and characterize
83 experimentally the spread and burning behaviors for the continuous spill fires using
84 surfaces with varying slope angles. A series of 15 continuous spill fire tests was carried
85 out on a rectangular surface. The real time burning area, the maximum and steady
86 burning area, burning rate and flame height were measured. The effects of the slope on
87 these parameters are discussed and analyzed.

88

89 **2. Experimental setup**

90 As depicted in Fig.1, an open rectangular trench was used in the tests with a
91 dimension of 6 m long by 0.8 m wide. The bottom is made of fireproof glass because it
92 can provide a perfectly flat surface, which can guarantee the even distribution of the
93 fuel layer on the surface as shown in Fig.2. The detail description of the experimental
94 platform is given in [17]. In the tests, the glass surface slope can be controlled and
95 adjusted by the six brackets installed under the trench, as shown in Fig.1 (d). The slope
96 angle was measured and examined before the start of each test by using a digital angle
97 ruler (BOSCHDNM60L). After the adjustment of the platform, preliminary tests
98 without ignition were conducted to ensure uniform spreading of the fuel. The detail
99 spread process is shown in Fig.2. During the tests, a peristaltic pump (WT600-3J) was
100 used to provide a steady volumetric flow rate ranging from 4.2 mL/min to 6000 mL/min.
101 An electronic balance was put under the fuel tank to record the mass loss rate and to
102 ensure that the peristaltic pump can provide a steady flow. The discharge rate was
103 calculated by mass loss measured by the electronic balance and the detail values for all
104 the tests are shown in Table.2.

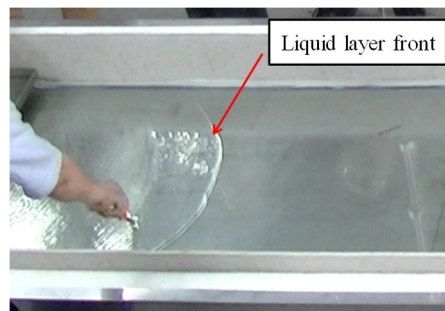


105

106 Fig. 1. Schematic diagram of the continuous spill fire experiment platform. a) Top

107

view; b) Sectional view; c) Structure of spill sump; d) Bracket.



108

109

Fig. 2. Liquid layer front after the levelling in a pre-test

110 In order to reduce the initial fuel velocity from tube, a spill flume was designed, in
 111 which the liquid fuel was introduced by gravity, shown in Fig.1 (c). In addition, some
 112 water layer was added in the sump to cut off the connection between the burning surface
 113 and the fuel tube to reduce the experimental risk. Two cameras were used to record the
 114 whole process and to determine the real time spread front position and the flame height.
 115 The camera one was located at a high place and the lens tilted at an angle so that the
 116 front of the liquid layer could be captured clearly. The other camera located at distance
 117 (~10m) to mainly record the flame height. Reference rulers in vertical and horizontal
 118 directions were used in experiments to calibrate the position of liquid layer front and
 119 the flame height, as illustrated in Fig. 3.

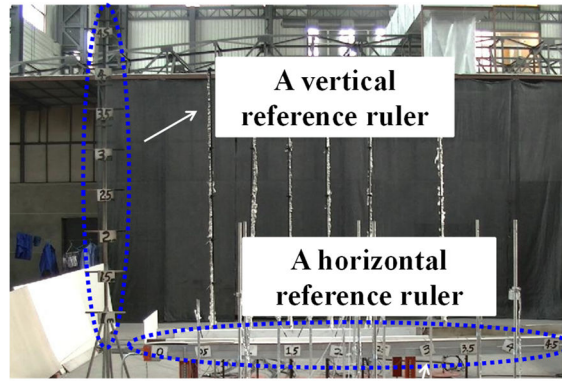


Fig. 3. The layout of the reference rulers in the tests

The flame shape was determined based on the difference between the flame and the background in red, green and blue (RGB) values of each pixel in pictures from the video recording, as commonly done in literature [e.g., 12,16-18]. A schematic diagram of the flame processing is given in Fig.4.

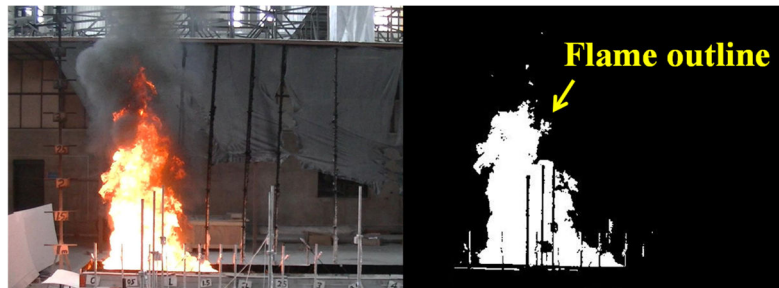


Fig. 4. A schematic diagram of the flame processing method ($R>200, G>100, B>50$)

In the tests, JP-4 was selected as the discharge fuel and a small amount of heptane (10 mL) was injected on the fuel surface to ignite the discharge fuel. As soon as the fuel spread on the glass surface, the heptane was ignited by an electric spark. The properties of JP-4 are shown in Table 1.

Table 1. The properties of JP-4 in tests [19]

Density (kg/m^3)	790
Burning rate of infinite diameter ($\text{kg/m}^2\text{s}$)	0.051
$k\beta$ value	3.6
Heat of combustion (MJ/kg)	43.5

The ambient temperature was around 26 ± 4 °C. The tests were conducted in a quiescent environment with no wind and at atmospheric pressure. The slope angle was

136 set from 0° to 3°. It is worth noting that larger slopes ($>3^\circ$) were also used in preliminary
 137 tests but it was found that the liquid layer could not spread uniformly in these tests
 138 because surface tension is overcome by gravity. The discharge rate can be controlled
 139 by the change of the rotation speed of the peristaltic pump. The detail experimental
 140 configurations are given in Table 2.

141 Table 2. Specification of the testing configurations

No.	$\theta(^{\circ})$	Revolutions per minute (rpm)	Discharge rate(L/min)	Discharge time(s)
Test-1	0	50	0.93	208
Test-2	0	100	2.05	201
Test-3	0	150	3.01	198
Test-4	0	200	4.39	202
Test-5	0.5	50	0.93	186
Test-6	0.5	100	2.05	194
Test-7	0.5	150	3.01	179
Test-8	0.5	200	4.39	180
Test-9	1	50	0.93	186
Test-10	1	100	2.05	191
Test-11	1	150	3.01	189
Test-12	1	200	4.39	176
Test-13	3	50	0.93	182
Test-14	3	100	2.05	191
Test-15	3	150	3.01	186

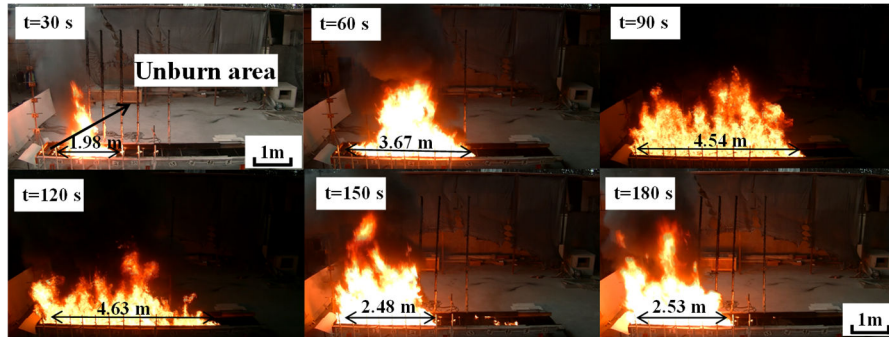
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143 3. Result and discussion

144 3.1 Spread process

145 The fuel started to spread on the rectangular glass surface as soon as the pump was
 146 turned on. Due to the difference in the discharge rate and the burning consumption
 147 (change in thickness per unit time \times spread area), the burning area varies significantly

148 with time for the whole spread process. In order to clearly display the whole spread
149 process, Test-8 ($Q_{in}=4.39$ L/min) is selected as an example to show the detailed spread
150 process in Fig. 5.



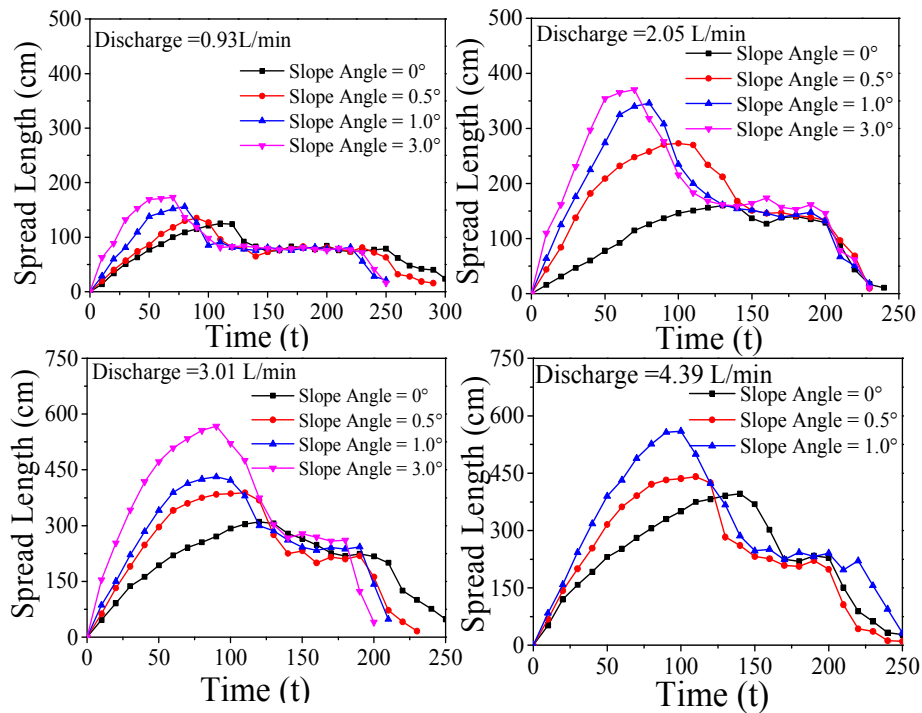
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152 Fig. 5. Images of continuous spill fire at some moments after discharge in Test 8

153 From the time of discharge $t=0$ s to the time $t=30$ s, we can observe that the fuel
154 spread fast and the flame only covers a small part of the liquid surface which means
155 that most of the fresh fuel was not burning in this period ($0s < t < 30s$). The flame was
156 small and gradually spread on the whole liquid surface in this period. As the spread
157 continues ($60s < t < 120s$), the burning area continued to increase and the spread length
158 reached its maximum (around 4.63 m) at $t=120$ s. In this period, the flame occupied the
159 whole liquid surface and the flame height also achieved the maximum value.
160 Considering the large burning area and flame height, we can conclude that the burning
161 consumption (burning area \times burning rate) played an important role in this period.
162 Subsequently, the burning area started to shrink due to the burning consumption higher
163 than the discharging rate, and reached a nearly constant value at around $t=150$ s,
164 corresponding to the equilibrium conditions, when the burning consumption becomes
165 the same as the discharging rate. These spread behaviors were also observed in the other
166 tests.

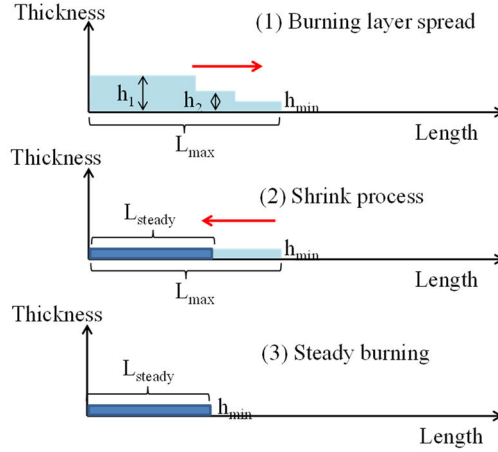
167 Figure 6 shows the real time front position of the liquid layer obtained by the video
168 analysis. The results indicate that the spread and burning behaviors can be characterized
169 by four distinct phases (namely burning layer spread, shrink process, steady burning
170 and extinguishment) appearing in succession in consistence with visual observations in
171 Fig. 5. The burning layer spread phase corresponds to the fire growth process in which
172 the burning area increases with time and the burning area reaches a maximum at the

173 end of this phase. The shrink phase corresponds to the decrease of the burning area due
 174 to the burning consumption larger than the fuel supply rate. The shrink phase is
 175 relatively short, which is followed by nearly constant burning area, which corresponds
 176 to the steady burning phase. Finally, after the stop of fuel supply, the fire gradually
 177 disappears in the extinguishment phase.



178
 179 Fig. 6. The front position of liquid layer as a function of time for some spill fire tests
 180 with different slope angles

181 Comparing the spread process on the different slopes, it can be observed that the
 182 division of the spread phase is independent of the slope angle. However, the detailed
 183 characteristics including the burning area, burning rate or spread rate in each phase are
 184 different and need to be discussed in detail. The phase division of whole spread process
 185 is meaningful to clearly know the development of continuous spill fire accidents and
 186 then further analyze the main physical mechanism related to spread and burning
 187 behaviors. In addition, the unbalance between discharge rate and burning consumption
 188 still exist, which determines these spread phases in the tests will be present in practical
 189 accidental spill fire scenarios. For clarity we summarize here the main spread process
 190 and the schematic is shown in Fig.7.



191

192 Fig. 7. The diagram of the main spread process (h_1 , h_2 and h_{min} are the fuel thickness
 193 at the different times, L is the fuel spread length)

194 In the simplified processes, the fuel thickness gradient with the spread length is not
 195 considered and this assumption has been widely used in some studies [20-22]. In the
 196 burning layer spread phase, gravity is a main force to drive the liquid layer spread,
 197 which is associated with the fuel thickness. And the real-time average thickness (h) can
 198 be expressed as:

$$199 \quad h = \frac{Q_{in}t - \int_0^t w(t)S(t)dt}{S} \quad (1)$$

200 where Q_{in} is the fuel discharge rate, S is the burning area, and $w(t)$ is the burning rate
 201 (thickness decrease per unit time, m/s). It has been confirmed in [7,22] that the liquid
 202 layer will stop spreading when the liquid layer thickness (h) equals to the minimum
 203 value (h_{min}) indicating the end of the burning layer spread phase. The minimum
 204 thickness is controlled by the balance between surface tension and gravity for spread
 205 on a flat surface [22-24]. The minimum thickness on a flat surface can be expressed as:

$$206 \quad h_{min} = \sqrt{\frac{2\sigma(1-\cos(\theta))}{\rho g}} \quad (2)$$

207 where ρ is the density of the fuel, θ is the contact angle, and σ is the surface tension.
 208 It should be noted that the above parameters need to be revised for ignited conditions
 209 in the quantitative analysis. For an inclined surface, this value will decrease with an
 210 increase in the slope as shown experimentally in [25,26], although the detailed value of
 211 the minimum thickness for an inclined surface is still unknown. For liquid layer spread,
 212 an empirical model has been provided by PHAST to calculate the spread rate on a flat

213 surface.

$$214 \quad \frac{dL}{dt} = k\sqrt{g(h - h_{min})} \quad (3)$$

215 where k is a spread constant ($k=2$) in a flat surface [27]. Based on Eqs.(1-3), it can be
216 concluded that the burning layer spread phase for continuous spread on a solid surface
217 is controlled primarily by the discharge rate, the burning rate and the minimum
218 thickness.

219 In the shrink process phase, there is no fresh fuel to supply to the front layer because
220 the burning consumption is larger than the discharge rate. In this phase, the thickness
221 of liquid layer reaches its minimum value. So the duration can be simplified under the
222 condition that the thickness gradient in the horizontal direction can be neglected as

$$223 \quad t_1 = \frac{h_{min}}{w_t} \quad (4)$$

224 In the steady burning phase, the burning area is nearly constant as the burning
225 consumption is the same as the discharge rate. Therefore the controlling equation in this
226 phase can be written as:

$$227 \quad w_{steady}S_{steady} = Q_{in} \quad (5)$$

228 where S_{steady} and w_{steady} are respectively the burning area and burning rate in the
229 steady burning phase. This method has been used in pool fires, in which the supply rate
230 equals to the burning consumption rate in the steady burning stage [26].

231 Table 3 shows that the duration of burning layer spread phase decreases with the
232 increase of slope for the tests with the same discharge rate. This can be explained by
233 examining Eqs.(1-3), where we have deduced that the spread rate will be higher on a
234 inclined surface due to the lower minimum thickness and gravity, which will result in a
235 quick decrease of the fuel thickness. Furthermore, the burning consumption also
236 increases due to the increasing burning surface area. The duration of the shrink phase
237 tends to decrease with the increase of slope, because the thickness will be shallower on
238 a larger slope surface. In the shrink process, there is no fresh fuel supplied to the front
239 layer due to a larger burning consumption and as a result, the shallower liquid layer will
240 lead to a shorter burning duration.

241 Table 3. The duration of burning layer spread and shrink process stages

Test	Spread stage duration (s)	Shrink stage duration(s)	Test	Spread stage duration (s)	Shrink stage duration(s)
1	116	38	9	82	29
2	128	35	10	86	25
3	134	40	11	107	29
4	152	39	12	110	27
5	96	31	13	65	18
6	106	36	14	76	22
7	107	33	15	82	21
8	126	37			

242

243 Figure 6 also shows that the burning area will change greatly with a change in the
 244 slope. The maximum burning area and the steady burning area are known as the two
 245 key parameters to determine the open fire damage and thermal hazard risk [2,28]. The
 246 values of the maximum (S_{max}) and steady burning areas (S_{steady}) obtained for all the tests
 247 are shown in Table 4. In addition, a ratio to define the relative difference between S_{max}
 248 and S_{steady} ($r_s = \frac{S_{max}-S_{steady}}{S_{steady}}$) is also introduced to show the range of variations.

249

Table 4. The maximum and steady burning area under different tests

No.	$S_{max}(m^2)$	$S_{steady}(m^2)$	r_s	No.	$S_{max}(m^2)$	$S_{steady}(m^2)$	r_s
Test-1	0.98	0.62	0.58	Test-9	1.59	0.69	1.30
Test-2	1.66	1.10	0.50	Test-10	2.42	1.10	1.20
Test-3	2.30	1.71	0.34	Test-11	3.36	1.56	1.16
Test-4	3.06	2.28	0.33	Test-12	4.38	2.24	0.95
Test-5	1.44	0.65	1.21	Test-13	1.75	0.72	1.43
Test-6	2.16	1.04	1.08	Test-14	2.93	1.29	1.27
Test-7	2.89	1.48	0.94	Test-15	3.85	1.70	1.26
Test-8	3.61	2.10	0.66				

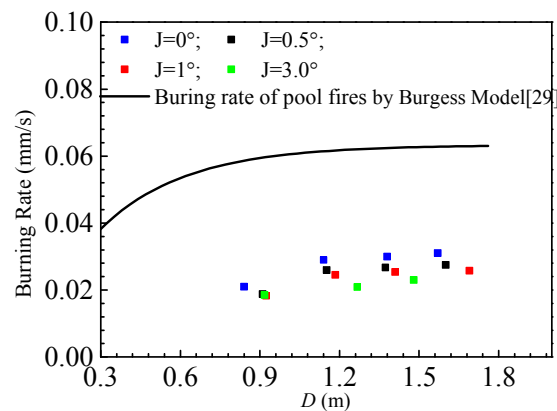
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251 Table 4 shows that both the maximum burning area and the steady burning area

252 increase with the increasing slope angle for the same discharge rate. However, it can be
253 observed that the maximum burning area is more sensitive to the slope angle compared
254 with the steady burning area. For example, comparing Test 1 and Test 5 the maximum
255 burning area increases by around 41.92%, while for the steady burning area, the
256 increase is less than 4.84%. This directly leads to the increase of r_s with the increase of
257 slope.

258 3.2 Burning rate

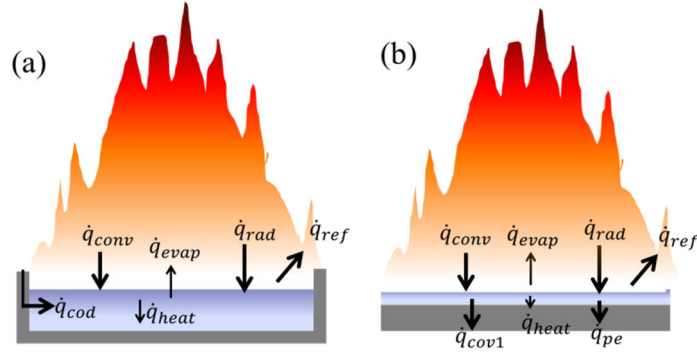
259 Although we can't measure the instantaneous burning rate, it is possible to calculate
260 using Eq.(5) the burning rate in the steady burning phase from the burning area and the
261 discharge rate. Fig.8 plot the steady burning rate as a function of the fire equivalent
262 diameter which is calculated based on the spread length and the width of trench. It can
263 be observed that the steady burning rate increases with the pool diameter. For
264 comparison, we also plot in Fig. 8 the burning rate calculated by the empirical
265 correlation developed from pool fires [29]. It is clear that, while the trends of both sets
266 of data are similar, the burning rate of a spilled fire is systematically lower than that of
267 a pool fire with the same pool diameter, which is in accordance with findings from
268 previous studies [1,3,12,13]. In order to explain this difference, it is important to
269 consider the difference in the heat transfer process between pool fires and spill fires as
270 illustrated in Fig. 9.



271

272

Fig. 8. A burning rate comparison for spill fires and pool fires



273

274 Fig. 9. Schematic of the main heat transfer mechanisms for (a) pool fire burning,
 275 adapted from Hamins et al.[30] and (b) spill fire burning

276 For pool fires, the heat feedback from the flame to the fuel surface is usually
 277 completely absorbed by the thick liquid layer and the heat loss between the liquid layer
 278 and the pan bottom is negligible [4]. So the burning rate of pool fires can be expressed
 279 as:

$$280 \quad \dot{w}' = \frac{\dot{q}_{rad} + \dot{q}_{cov} + \dot{q}_{cod} - \dot{q}_{ref}}{\rho(c_{pf}\Delta T + L_v)} \quad (6)$$

281 where c_{pf} is fuel specific heat capacity and L_v is latent heat of evaporation. For a large
 282 burning area ($D > 0.2$), the heat conduction from the side walls to the liquid layer (\dot{q}_{cod}),
 283 the radiative reflection (\dot{q}_{ref}) and the heat convection (\dot{q}_{cov}) between the flame and the
 284 liquid surface are usually neglected [30]. So an empirical model based on the radiative
 285 heat feedback from flame to surface was proposed by Burgess [29].

$$286 \quad \dot{w}'_{pool} = w'_{\infty}(1 - e^{-k\beta D}) \quad (7)$$

287 where w'_{∞} is the burning rate of an ‘infinite’ pool diameter (burning thickness per
 288 time), k is an absorption extinction coefficient, and β is a mean beam length corrector.

289 In the test, the heat loss of liquid layer is considered as the main reason behind the
 290 lower burning rate. The heat loss of liquid layer can be divided into two parts: the
 291 radiative penetration (through the liquid layer and the glass) and the heat transfer from
 292 the liquid layer to the glass including the convection and conduction. For the burning
 293 of pool fires, the radiative heat flux is mainly absorbed by the upper liquid layer (~3mm),
 294 which results in a thin boiling layer [31]. However, the initial thickness was estimated
 295 based on preliminary spread tests (no ignition) to be less than 2 mm in the present tests,
 296 which illustrates that the radiative heat feedback cannot be completely absorbed by the

297 spread layer, as verified in our previous studies [17,32]. In fact, the radiative heat
 298 feedback can also be divided into two parts: unabsorbed part (q_{non-ab}) and absorbed
 299 part (q_{ab}) in previous studies [31,32]. The radiative heat loss of the liquid layer can be
 300 expressed as:

$$301 \quad q_{radloss} = q_{non-ab} + \varepsilon q_{ab} e^{-ah} \quad (8)$$

302 where a is an absorption coefficient, h is the thickness of the liquid layer and ε is the
 303 transmittance ratio of the fireproof glass.

304 The heat transfer process between the liquid layer and the glass will be more obvious
 305 due to the thin liquid layer and the movement of the fuel. In the quantitative analysis, it
 306 is difficult to directly calculate this heat loss part due to the coupling effects of radiation
 307 and fuel movement. However, the temperature of the bottom glass can represent the
 308 heat transfer process in qualitative because the radiation effect on the glass temperature
 309 increase can be neglected. Therefore, the transfer heat flux between the liquid layer and
 310 the glass surface due to the convection and the heat conduction can be expressed as:

$$311 \quad q_{loss2} = mc_{pglass}\Delta T \quad (9)$$

312 where m is the glass mass per unit area in the tests, c_{pglass} is the specific heat of the
 313 glass at the atmospheric pressure and ΔT is the temperature increasing rate of the glass.
 314 Combining Eqs.(6-9), the burning rate of continuous spill fires can be deduced as:

$$315 \quad \dot{w}'_{spill} = \left(1 - \frac{q_{radloss} + q_{loss2}}{\dot{q}_{rad}}\right) w'_{\infty} (1 - e^{k\beta D}) \rho \quad (10)$$

316 In the steady burning phase, the fuel thickness has achieved the minimum value,
 317 which directly determines the stable of the liquid layer radiative heat loss. In addition,
 318 we found that the bottom glass surface temperature nearly kept a constant in the tests,
 319 gradually approaching the boiling point at the steady burning phase, which has been
 320 observed in [17]. The variation trend of the glass temperature illustrates the transfer
 321 process can be approximately considered as a stable process. As a result, the steady
 322 burning area in Fig.6 and stable burning rate in Fig.8 can be observed in the tests.

323 As mentioned earlier, the increase of the slope angle can lead to a thin liquid layer,
 324 which would indicate based on Eq.(8) that $q_{radloss}$ will increase and subsequently a
 325 lower burning rate. This is verified in Fig. 8, which shows that for the same discharge

326 rate the larger the slope angle, the smaller the burning rate in the steady phase. In order
 327 to compare the burning rate of between the spill fire and pool fire quantitatively, the
 328 ratio ($\dot{m}'_{spill}/\dot{m}'_{pool}$) is given in Table 5.

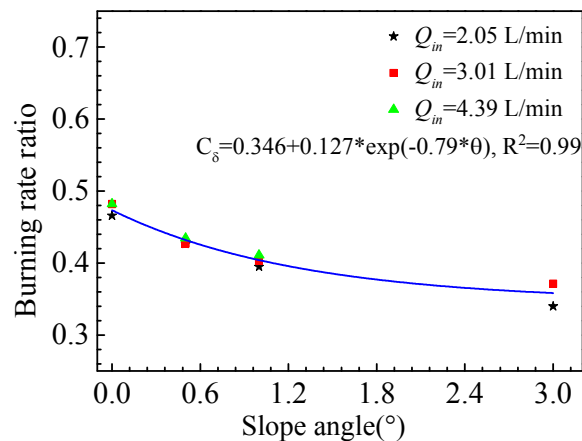
329 Table 5. The burning rate ratio the same burning size

	$Q_{in}=0.93\text{L/min}$	$Q_{in}=2.05\text{ L/min}$	$Q_{in}=3.01\text{ L/min}$	$Q_{in}=4.39\text{ L/Min}$
$\theta=0^\circ$	0.3555	0.4661	0.4819	0.4819
$\theta=0.5^\circ$	0.316	0.4266	0.4266	0.4345
$\theta=1.0^\circ$	0.3081	0.395	0.4029	0.4108
$\theta=3.0^\circ$	0.3002	0.3397	0.3713	Non

330

331 Table 5 shows that the burning rate of spill fires is systematically lower than that of
 332 pool fires and the burning rate ratio of spill fires to pool fires is from 0.30 to 0.49. For
 333 the tests with the smallest discharge rate of 0.93 L/min, this ratio is the smallest. We
 334 believe that this is because relative importance of the conduction heat loss in the
 335 horizontal direction in the glass is more important in these cases as the spread length is
 336 much smaller than those with large discharge rates. This would suggest less energy is
 337 available for fuel evaporation. With the increasing fuel discharge rate (and spread
 338 length), the importance of this part of heat loss, when compared to the total heat
 339 feedback ($S \times q_f$) from the flame to the liquid layer, will gradually decrease and
 340 eventually becomes negligible as we noted in Table 5 that the ratio for higher discharge
 341 rates is nearly the same for the same slope angle.

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Fig. 10. The burning rate ratio vs the slope angle

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Figure 10 shows the variation of the burning rate ratio with the slope angle except for the case with $Q_{in}=0.93\text{L}/\text{min}$ due to its small burning size. All the test data collapse into one single line. The fact that the burning rate ratio becomes nearly constant can be explained by examining the change of the thickness of the liquid layer with the slope angle. With the increasing of slope, the decrease of liquid fuel thickness will gradually become smaller due to the fuel surface tension limitation [33,34]. We have shown that the burning rate of spill fires is mainly affected primarily by the fuel thickness. This explains that the burning rate ratio initially decreases with the slope angle but then gradually approaches a constant when the slope angle becomes sufficiently large as shown in Fig.10. It should be noted however that we expect that the relation only holds up to a certain slope angle because if the slope angle becomes too large, the surface tension will be overcome by gravity and the fuel will not spread evenly on the glass surface, resulting in a discontinuous spread area, as we found in some preliminary tests.

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3.3 Flame height

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Flame height is a key parameter in the liquid fire and is closely related to the surrounding radiative distribution [4,9]. The flame height was determined by analyzing the digital images as discussed earlier. Fig.11 shows the experimental results of the flame height as a function of time for the case with the discharge rate of 2.05 L/min. The flame height in the whole spread process experiences the following four stages: quick increase, slow decrease, stable and extinguishment. The initial flame height was due to the burning of the ignition source. In general, the flame height variation is consistent with that of the burning area change. The ignition of JP-4 was identified as the appearance of strong black smoke.

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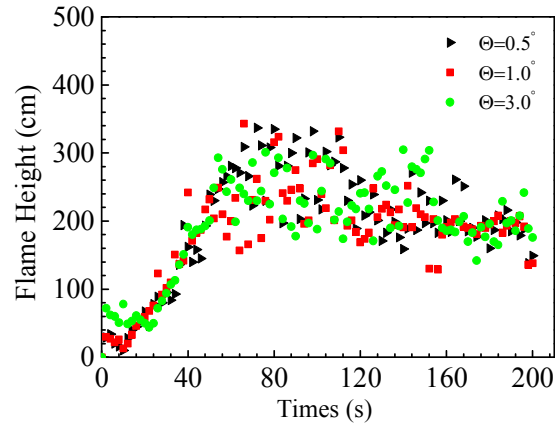
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It is interesting to note that in the steady burning phase, the flame heights nearly keep constant for the same discharge rate independent of the slope. This is due to the fact that the burning area and the burning rate at the steady burning phase are almost the same for the cases with different slopes but the same discharge rate. However, the flame fluctuations are significant for tests with large slope angles. As mentioned above, the

374 liquid layer is thin on a large slope angle surface, which results in unsteady burning.



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Fig. 11. The variation of the flame height as a function of time under the

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different slopes ($Q_{in}=2.05$ L/min)

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In the steady burning phase, the ratio of fire length to fire width is less than three and the burning area can approximately consider as a circle pool fire. We can calculate the flame height following as [35]:

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$$H/D = 3.7\dot{Q}^{*2/5} - 1.02 \quad (11)$$

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where D is the equivalent burning diameter ($2\sqrt{WL/\pi}$), \dot{Q}^* is the dimensionless heat release rate which is defined as:

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$$\dot{Q}^* = \frac{\dot{Q}}{\rho_0 c_{pa} T_0 g^{0.5} D^{5/2}} \quad (12)$$

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where ρ_0 and T_0 are ambient density and temperature, respectively. g is the gravity acceleration. c_{pa} is the specific heat of air at constant pressure and \dot{Q} is the total heat release rate, which is calculated as:

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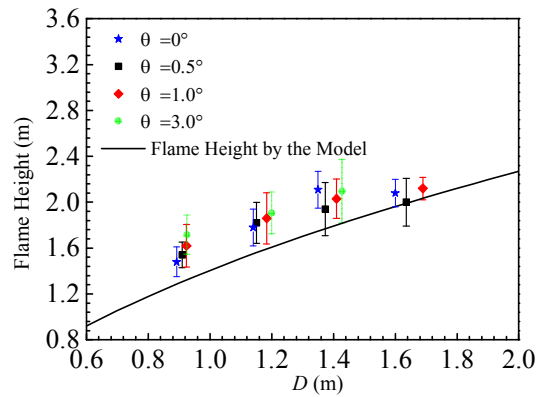
$$\dot{Q} = C_\delta \dot{m}_{pool} H_c \quad (13)$$

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where C_δ is a modified coefficient (a ratio between the spill fire burning rate and the pool fire burning rate) and its values are given in Table 5 for all the tests. Fig. 12 shows a comparison of the experimental and calculated flame height. It can be seen that the flame height model can predict well the spill fire flame height with the modified heat release rate. The predicted flame heights are generally slightly lower than the experimental values. This could be due to the non-uniform burning rate on the whole burning surface as we observed that during the tests the burning near the front and back

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396 of the spill pool is less intense than that in the center region. This implies that the
 397 equivalent pool diameter is overestimated by the model and as a result based on Eq.(11)
 398 underestimated flame height.



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 400 Fig. 12. The calculated flame height with respect to the burning diameter in
 401 comparison with the measured values in tests

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403 4. Conclusion

404 The spill fires experiments with different discharge rates were conducted on a
 405 rectangular glass surface with varied slope angles. The effects of the slope on the spread
 406 and burning behaviors are analyzed and summarized.

407 For the spread behaviors of spill fires, the whole spread process can be divided into
 408 four phase: 1) burning layer spread phase; 2) shrink phase; 3) steady burning phase and
 409 4) extinguishment, independent of the slope angle. However, the duration and the
 410 burning area vary greatly with the slope angle. The durations of the burning layer spread
 411 phase and shrink phase decrease with the increase in the surface slope angle. It was also
 412 found that the slope has a more important effect on the maximum burning area than the
 413 steady burning area, resulting in an increase of the relative difference, $r_s = \frac{S_{max} - S_{steady}}{S_{steady}}$
 414 with increasing slope angle.

415 For the burning behavior, the burning rate of a spill fire was found to be
 416 systematically lower than that of a pool fire for the same burning size and the burning
 417 rate ratio ranges from 0.30 to 0.49. It was found that the spill fire burning rate at the
 418 steady burning phase decreased with an increase of the slope angle because the shallow
 419 liquid fuel would result in a large heat loss of the liquid layer. The burning rate ratio

420 between the spill fire and corresponding pool fire was introduced to characterize the
421 effects of slope on the burning rate and it was found that the burning rate ratio initially
422 decreases with the slope angle but then approaches a nearly constant for large slopes
423 because of the smaller variation of the fuel thickness with an increase of the slope angle.
424 A correlation between the burning rate ratio and slope angle is also deduced.

425 The flame height in the steady burning phase was found to increase with increasing
426 equivalent fire diameter. It was also shown that the flame height correlation developed
427 for pool fires can be used to predict spill fires after the heat release rate is modified
428 using the burning rate ratio, provided that the ratio of fire length to fire width is less
429 than three.

430 We have presented in this work a detailed study of the effects of the slope on the
431 spread and burning behaviors of continuous spill fires. The analysis of the spread
432 process and the determination of some key parameter can provide some guidance in
433 thermal hazard risk assessment in actual spill fire accidents. Moreover, the
434 experimental data can be used to further develop numerical models for prediction of
435 continuous spill fires. However, more experiments, especially on different substrates,
436 should be conducted to address the continuous spill fire issue.

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444 **References**

- 445 [1] C. Mealy, M. Benfer, G. Dan, Liquid Fuel Spill Fire Dynamics, *Fire Technol.*, 50
446 (2014), pp. 419-436.
- 447 [2] S. Brambilla, D. Manca, Accidents involving liquids: A step ahead in modeling pool
448 spreading, evaporation and burning. *J. Hazard. Mater.*, 161(2-3)(2009), pp. 1265-1280.
- 449 [3] D.T. Gottuk, D.A. White. Liquid fuel fires. In: SFPE handbook of fire protection

450 engineering. Springer, New York, NY, 2016, pp. 2552-2590.

451 [4] D. Drysdale. An introduction to fire dynamics. John Wiley & Sons, 2011.

452 [5] G. Landucci, G. Gubinelli, G. Antonioni, et al. The assessment of the damage
453 probability of storage tanks in domino events triggered by fire. *Accident Anal. Prev.*,
454 41(6)(2009), pp. 1206-1215.

455 [6] Z. Ni, Y. Wang, Z. Yin. Relative risk model for assessing domino effect in chemical
456 process industry. *Safety Sci.*, 87(2016), pp. 156-166.

457 [7] D.W. Hissong. Keys to modeling LNG spills on water. *J. Hazard. Mater.*,
458 140(3)(2007), pp. 465-477.

459 [8] F. Briscoe, P. Shaw. Spread and evaporation of liquid. *Prog. Energy Combust. Sci.*,
460 6(2)(1980), pp. 127-140.

461 [9] J. Ji, X. Yuan, K. Li, et al. A mathematical model for burning rate of n-heptane pool
462 fires under external wind conditions in long passage connected to a shaft. *Appl. Therm.*
463 *Eng.*, 116(2017), pp. 91-99.

464 [10] B.D. Ditch, J.L. de Ris, T.K. Blanchat, et al. Pool fires-An empirical correlation.
465 *Combust. Flame*, 160(12)(2013), pp. 2964-2974.

466 [11] M. Benfer. Spill and Burning Behavior of Flammable Liquids. Master Dissertation,
467 School of Maryland, 2010.

468 [12] Y. Li, H. Huang, Z. Wang, et al. An experimental and modeling study of continuous
469 liquid fuel spill fires on water. *J. Loss Prev. Process Ind.*, 33(2015), pp. 250-257.

470 [13] Y. Li, H. Huang, J. Zhang, et al. Large-scale experimental study on the spread and
471 burning behavior of continuous liquid fuel spill fires on water. *J. Fire Sci.*, 32(5)(2014),
472 pp. 391-405.

473 [14] S. Raja, T. Abbasi, S.M. Tauseef, et al. Equilibrium models for predicting areas
474 covered by accidentally spilled liquid fuels and an assessment of their efficacy. *Process.*
475 *Saf. Environ.*, 130(2019), pp. 153-162.

476 [15] H. Ingason, Y.Z. Li. Spilled liquid fires in tunnels. *Fire Safety J.*, 91(2017), pp.
477 399-406.

478 [16] Y. Li, H. Huang, L. Zhang, et al. An experimental investigation into the effect of
479 substrate slope on the continuously released liquid fuel spill fires. *J. Loss Prev. Process*

480 Ind., 45 (2017): pp. 203-209.

481 [17] J. Zhao, Q. Liu, H. Huang, et al. Experiments investigating fuel spread behaviors
482 for continuous spill fires on fireproof glass. *J. Fire Sci.*, 35(1)(2017), pp.80-95.

483 [18] Y. Lin, M.A. Delichatsios, X. Zhang, et al. Experimental study and physical
484 analysis of flame geometry in pool fires under relatively strong cross flows. *Combust.*
485 *Flame*, 205(2019), pp. 422-433.

486 [19] V. Babrauskas. Estimating large pool fire burning rates. *Fire Technol.*,19(4) (1983),
487 pp.251-261.

488 [20] D.W. Johnson, J.B. Cornwell. Modeling the release, spreading, and burning of
489 LNG, LPG, and gasoline on water. *J. Hazard. Mater.*, 140(2007), pp. 535-540.

490 [21] W. Lehr, D. Simecek-Beatty. Comparison of hypothetical LNG and fuel oil fires
491 on water. *J. Hazard. Mater.*, 107(2004), pp. 3-9.

492 [22] J.M. Raisbeck, M.F. Mohtadi. The environmental impacts of oil spills on land in
493 the arctic regions. *Water Air Soil Poll.*, 3(2)(1974), pp. 195-208

494 [23] M. Hussein, M. Jin, J.W. Weaver. Development and verification of a screening
495 model for surface spreading of petroleum. *J. Contam. Hydrol.*, 57 (2002) , pp281-302.

496 [24] C.S. Simmons, J.M. Keller, J.L. Hylden. Spills on flat inclined pavements.
497 Department of Energy, United States, 2014.

498 [25] T. Abbasi, V. Kumar, S.M. Tauseef, et al. Spread rate of flammable liquids over
499 flat and inclined porous surfaces. *J. Chemical Health and Safety*, 25(5)(2018), pp. 19-
500 27.

501 [26] A. Sharma, K.B. Mishra. Experimental set-up to measure the maximum mass
502 burning rate of storage tank fires. *Process Saf. Environ.*, 131(2019), pp.282-291.

503 [27] H.W.M. Witlox. Model for pool spreading, evaporation and solution on land and
504 water (PVAP)-Theory Manual, Consequence modeling documentation (PHAST
505 Technical Reference), 2000.

506 [28] J. Zhao, H. Huang, Y. Li, et al. Quantitative risk assessment of continuous liquid
507 spill fires based on spread and burning behaviors. *Appl. Therm. Eng.*, 126(2017), pp.
508 500-506.

509 [29] D.S. Burgess, A. Strasser, J. Grumer. Diffusive burning of liquid fuels in open trays.

510 Fire Res. Abstr. Rev., 1961.

511 [30] A. Hamins, S.J. Fischer, T. Kashiwagi, et al. Heat feedback to the fuel surface in
512 pool fires. *Combust. Sci. Technol.*, 97(1-3)(1994), pp. 37-62.

513 [31] J.M. Suo-Anttila, T.K. Blanchat, A.J. Ricks, et al. Characterization of thermal
514 radiation spectra in 2 m pool fires. *Combustion Inst.*, 32 (2009), pp. 2567-2574.

515 [32] J. Zhao, H. Huang, H. Wang, et al. Experimental study on burning behaviors and
516 thermal radiative penetration of thin-layer burning. *J. Therm. Anal. Calorim.*, 130
517 (2017), pp. 1153-1162.

518 [33] G. Kirstetter, J. Hu, O. Delestre, et al. Modeling rain-driven overland flow:
519 Empirical versus analytical friction terms in the shallow water approximation. *J.*
520 *Hydrol.*, 536(2015), pp. 1-9.

521 [34] J.R. Lister. Viscous flows down an inclined plane from point and line sources. *J.*
522 *Fluid Mech.*, 242(1992), pp. 631-653.

523 [35] B. McCaffrey, Flame Height. *The SFPE Handbook of Fire Protection Engineering*,
524 2nd ed., Society of Fire Protection Engineers and National Fire Protection Association,
525 Quincy, MA, 1995.