〈Invited Review Article〉

Recent Progress of Spray-Wall Interaction Research

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In the present article, recent progress of spray-wall interaction research has been reviewed. Studies on the spray-wall interaction phenomena can be categorized mainly into three groups: experiments on single drop impact and spray (multiple-drop) impingement, and development of comprehensive models. The criteria of wall-impingement regimes (i.e., stick, rebound, spread, splash, boiling induced breakup, breakup, and rebound with breakup) and the post-impingement characteristics (mostly for splash and rebound) are the main subjects of the single-drop impingement studies. Experimental studies on spray-wall impingement phenomena cover examination of the outline shape and internal structure of a spray after the wall impact. Various prediction models for the spray-wall impingement phenomena have been developed based on the experiments on the single drop impact and the spray impingement. In the present article, details on the wall-impingement criteria and post-impingement characteristics of single drops, external and internal structures of the spray after the wall impact, and their prediction models are reviewed.

Key Words : Single Drop Impact, Impingement Regime Criteria, Post-Impingement Characteristics, Spray Outline, Spray Internal Structure, Heat Transfer Performance, Spray-Wall Interaction Model

Nomenclature

a	: Ratio of the flattening velocity to the impact velocity (V_{fla}/V)	[−]
c_p	: Specific heat	[J/kgK]
d	: Droplet diameter	[m]
e	: Restitution coefficient	[−]
f	: Frequency	[1/s]
G	: Liquid mass flux	[kg/m²s]
h	: Convective heat transfer coefficient	[W/m²K]
H	: Height	[mm]
i	: Enthalpy	[J/kg]
K	: Sommerfeld number ($=We^{0.5}\cdot Re^{0.25}$)	[−]
K'	: Modified Sommerfeld number ($=We^{0.8}\cdot Re^{0.4}$)	[−]
K_f	: Splashing parameter ($=0.5\cdot a^{1.25}\cdot Re^{-0.3}\cdot K$)	[−]
k	: Thermal conductivity of liquid droplet	[W/mK]
La	: Laplace number ($=\rho_l\cdot\sigma\cdot d/\mu^2$)	[−]
L	: Length scale	[m]
m	: Droplet mass	[kg]
N	: Number of secondary droplets	[−]
Nu	: Nusselt number ($=h\cdot d/k$)	[−]
n	: Number of droplets in a parcel	[−]
Oh	: Ohnesorge number ($=\mu/(\rho_l\cdot\sigma\cdot d)^{0.5}$)	[−]
P	: Pressure	[MPa]
Pr	: Prandtl number ($=\nu/\alpha_l$)	[−]
q''	: Heat flux	[W/m²]
R	: Radius	[mm]
$RN(0,1)$	: Random number distributed uniformly in the interval (0, 1)	[−]

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Re : Drop Reynolds number based on the normal velocity ($=\rho_l \cdot V_{b,n} \cdot d/\mu$) [−]
r : Radius [m]
T : Temperature [K]
t : Time [ms]
u : Non-dimensional impact velocity [−]
V : Droplet velocity [m/s]
We : Droplet Weber number based on the normal velocity ($=\rho_l \cdot V_{b,n}^2 \cdot d/\sigma$) [−]

Greek

α : Contact angle at the maximum extension of the drop [°]
α_l : Thermal diffusivity of liquid droplet [m^2/s]
α_w : Wall inclination angle [°]
δ : Film thickness [m]
ΔP : Pressure drop between injection pressure and back pressure [MPa]
ΔT_{sat} : Superheat temperature difference ($=T_w - T_{sat}$) [K]
ΔT_{sub} : Subcooling of the droplet ($=T_{sat} - T_l$) [K]
ε : Spray heat transfer effectiveness [−]
ϕ : Curvature radius of film [m]
λ : Surface roughness [m]
μ : Liquid viscosity [$N \cdot s/m^2$]
ν : Kinematic viscosity [m^2/s]
θ : Incident angle [°]
ρ : Liquid density [kg/m^3]
σ : Liquid surface tension [N/m]
τ : Dimensionless time [−]
$\forall$: Volume [m^3]
ω : Deflection angle [°]

Subscripts

a : After impingement
amb : Ambient
B : Boiling
b : Before impingement
c : Crtical
d : Droplet
f : Film
fla : Flattening
I : Impact
i : Index
imp : Impingement
Leid : Leidenfrost
l : Liquid phase
lv : Difference between gas and liquid
N : Nukiyama
n : Normal
nd : Non-dimensional
PA : Pure adhesion
PR : Pure rebound
R : Rebound
s : Spray
sat : Liquid saturation properties
sp : Splash
sub : Subcooling
t : Tangential
v : Vapor phase
w : Wall
x1 : Upstream
x2 : Downstream
30 : Volume mean

Superscripts

$\bar{}$: Average

1. Introduction

Spray-wall interaction phenomenon is observed in spray painting, spray cooling, spray printing, direct injection (DI)-type internal combustion (IC) engine, spray coating, steel rolling, electronics cooling, and agricultural sprays. Drop/spray behavior (sizes and velocities of drops, spray outlines, etc.) and liquid film formation subsequent to impingement as well as the wall heat transfer are strongly dependent on the velocities and sizes of drops, wall surface conditions, and the fluid properties as illustrated in Fig. 1.

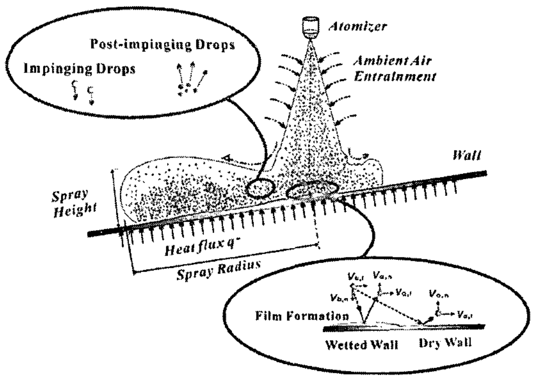

Fig. 1 Overall structure of spray-wall interaction

The spray-wall interaction phenomenon has been a subject of interest for a long time due to its wide applications and the academic interest. Previous studies regarding the phenomenon can be classified into three main categories as follows:

- Single drop impact
- Experiments on wall impingement of sprays (multiple drops)
- Modeling of wall impingement of sprays

Similar categories have been stated by Tropea and Marengo (1999). Basic studies on the single drop impact form a foundation for prediction and modeling of spray behavior. On the other hand, as a global approach, the wall impingement phenomena of sprays (multiple drops) have been studied experimentally. Based on the information on the single drop impact and experimental observation of sprays, the impingement of multiple numbers of drops on solid walls is modeled by taking account of the drop interactions.

In this article, the recent progress of the spray-wall interaction research for the aforementioned three categories is reviewed.

2. Single Drop Impact

The studies on the single drop impact, can be divided into two groups: classification of impingement regimes and post-impingement characteristics of the drops. In practice, post-impingement characteristics are represented by sizes and velocities of secondary drops subsequent to the wall impingement and the heat transfer behavior through evaporation and boiling of drops.

2.1 Criteria of drop impingement regimes

Hydrodynamic behavior of drops after the wall impact is governed by the heating condition (surface temperature) as well as the characteristics of impinging drops such as velocity, size and the liquid properties. Naber and Farrell (1993) identified three hydrodynamic regimes (contact (wetting), transition and non-contact (non-wetting) regimes) and four heat transfer regimes (film evaporation, vaporization/boiling, transition, Leidenfrost) based on the wall surface temperature. Figure 2

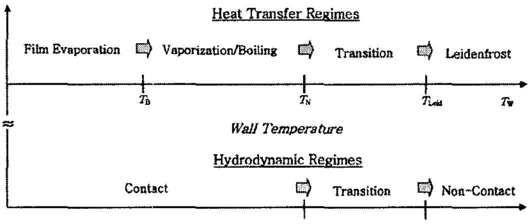

Fig. 2 Heat transfer and hydrodynamic regimes (based on Naber and Farrell, 1993)

illustrates the relationship between the hydrodynamic regimes and the heat transfer regimes for a drop impinging on a heated surface. In the contact regime, the liquid drop is in complete contact with the wall. This regime appears at low surface temperature, mostly below the Nukiyama temperature (T_N). (Naber and Farrell, 1993) In the non-contact regime, the drop is levitated above the wall surface when a vapor film is formed beneath the drop. This phenomenon occurs at a temperature higher than the Leidenfrost temperature (T_{Leid}). (Naber and Farrell, 1993; Chandra and Avedisian, 1991) The transition regime exists between the contact and non-contact regimes, where the liquid drop touches the heated wall intermittently by occasional formation of the vapor film. (Naber and Farrell, 1993) The work of Chandra and Avedisian (1991) showed that the hydrodynamic regimes are strongly dependent on the surface temperature.

In addition, the impingement regime is determined by the wall surface characteristics, such as dry/wet state and thickness of the liquid film (if any), surface roughness/wettability and wall porosity. (Bai and Gosman, 1995; Tropea and Marengo, 1999) In the following sections, various aspects of the wall impingement of drops are summarized.

2.1.1 Dry-wall impingement

Bai and Gosman (1995) identified seven different impingement regimes for a single drop impacting on a dry wall in terms of the Weber number and the surface temperature, namely, stick, rebound, spread, splash, boiling induced breakup, breakup and rebound with breakup. Figure 3 illustrates a modification of the map by Bai and

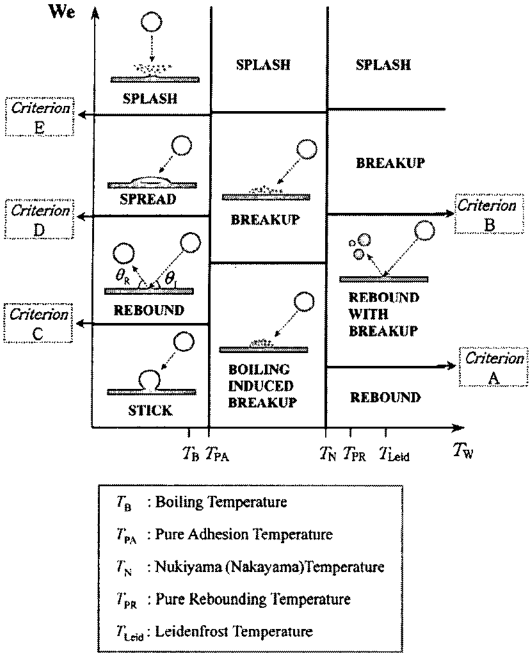

Fig. 3 Overview of droplet impingement regimes for dry walls (based on Bai and Gosman, 1995)

Gosman (1995), where the rebound regime is additionally included in the low temperature range, below the pure adhesion (or boiling) temperature. Note that the rebound regime was not observed below the boiling surface temperature in the original work of Bai and Gosman (1995).

Regarding the regime map, quantification of the each boundary has a practical importance; actually, the boundary lines are not straight and depend also on many other parameters such as surface characteristics and the properties of the liquid drop. Equations (1)-(8) in Table 1 are the criteria of impingement regimes of a single drop at a dry wall. Also, criteria A to E in Table 1 are in consistence with the regime boundaries depicted in Fig. 3.

2.1.1.1 Transition criteria in non-contact regimes

For surfaces at higher than the Leidenfrost temperature ($T_W > T_{Leid}$), the criteria A and B, have

Table 1 Criteria of impingement regimes for dry walls

Boundary	Reference	Criterion	Remarks
A (Rebound/Rebound with Breakup)	Wachters and Westerling (1966)	$We_c=30$ $(We=\rho_l \cdot V_{b,n}^2 \cdot d/\sigma)$ (1)	- $T_{Leid}<T_w$ - Substrate : polished gold cylinder - Liquid : water et al. - $d=2$ mm
B (Rebound with Breakup/Breakup)		$We_c=80$ (2)	
C (Stick/Rebound)	—	$We \ll 1$ (3)	Occurs at very low impact energy
D (Rebound/Spread)	Yoon et al. (2006)	$We/(Re)^{0.5}=\frac{3}{4}(1-\cos\alpha)$ (4)	Based on the energy analysis
E (Spread/Splash)	Bai and Gosman (1995)	$We_c=A \cdot La^{-0.18}$ (5) $(La=\rho_l \sigma d/\mu^2)$ $\bar{\lambda}(\mu m)$: 0.05, 0.84, 12 A: 5264, 2634, 1322	- $d=3.4$ mm - $1.5\times10^{-5}<\lambda_{nd}<3.5\times10^{-3}$
	Mundo et al. (1995)	$K=57.7$ (6) $(=We^{0.5}Re^{0.25})$	- $60<d<150$ μm - $\lambda_{nd}=0.03$, 0.86
	Cossali et al. (1997)	$K'=649+3.76\lambda_{nd}^{-0.63}$ (7) $(K'=We^{0.8}Re^{0.4})$ $\lambda_{nd}(=\bar{\lambda}/d)$	- $1.5\times10^{-5}<\lambda_{nd}<0.86$
	Fukumoto el al. (2002)	$K_f\approx7$ (8) $(K_f=0.5a^{1.25}Re^{-0.3}K,\ a=V_{fla}/V)$	Thermal spray particles : Ni, Cu, Fe

been reported by Wachters and Westerling (1966). They visualized behavior of a drop impinging on a wall at 400℃, and the boundaries between those criteria were expressed simply in critical Weber numbers (We_c) as Eqs. (1) and (2), respectively. Here, the regime between the criteria A and B (i.e., rebound with breakup) is considered to be the transition stage between the rebound and the breakup regimes. To the authors' knowledge, no specific correlation has been reported for the breakup/splash criterion in the non-contact regime. This may be because, in practice, the drop behavior in the breakup regime is very similar to that in the splash regime.

2.1.1.2 Transition criteria in contact regimes

In this section, the transition criteria C, D and E for the wall temperature condition of $T_W > T_{PA}$ were introduced.

Stick-Rebound Boundary (Criterion C): Occurrence of the rebound regime has been briefly reported by Sikalo et al. (2005) They reported that the drop bounces on a dry smooth glass (say, $\lambda=0.003$ microns) even at the low surface temperature condition because of presence of a thin air film between the drop and the glass surface. However, with a rough surface ($\lambda=3.6$ microns), the drop may be in contact with the local (micron-size) peaks of the surface and the rebound phenomenon is not likely to occur. According to the observation of Sikalo et al. (2005), the rebound regime existed below the spread regime, and considering that the drop spread occurs at We=1.03 for water and We=3.25 for isopropanol, the boundary C is expected to exist at far below those Weber numbers as Eq. (3) in Table 1.

Rebound-Spread Boundary (Criterion D): The lower boundary of the spread regime has been proposed by Yoon et al. (2006) based on the energy analysis. That is, under the impact state, the drop bounces when the drop surface energy becomes larger than the viscous dissipation energy. It should be noted that Eq. (4) in Table 1 is somewhat different from the original equation of Yoon et al. (2006), where a slight mistake was made in the derivation process (Yoon, 2006). Mao et al. (1997) also have attempted a similar approach.

Spread-Splash Boundary (Criterion E): The spread-splash boundary has been a subject of interest to automotive engineers for the reason of a poor mixing and low combustion efficiency in DI-type IC engines when a liquid (fuel) film is formed by spread of drops. Several works have been reported regarding the criterion E, such as by Bai and Gosman (1995), Mundo et al. (1995) Cossali et al. (1997) and Fukumoto et al. (2002), taking into account the surface conditions and the liquid properties. Based on the experiments by Stow and Hadfield (1981), Bai and Gosman (1995) proposed Eq. (5) for the critical Weber number in terms of the wall surface roughness and the Laplace number (La). According to them, the splash occurs even at the relatively low Weber number when the surface roughness and/or the Laplace number are relatively high. Mundo et al. (1995) reported that the criterion E depends on the Reynolds number as well as the Weber number. They proposed a simple correlation as Eq. (6) using the Sommerfeld number K ($=We^{0.5}Re^{0.25}$) for normalized surface roughness ($\lambda_{nd}=\bar{\lambda}/d$) of 0.03 and 0.86. However, later on, Cossali et al. (1997) proposed Eq. (7) for the criterion E that covers a wider range of the surface roughness, $1.5\times10^{-5}\leq\lambda_{nd}\leq0.86$, also mostly based on the experimental data by Stow and Hadfield (1981) and Mundo et al. (1995), and introduced the modified Sommerfeld number K' ($=We^{0.8}Re^{0.4}=K^{1.6}$). Figure 4 compares Eqs. (5), (6) and (7) in terms of K as a function of the surface roughness. It shows the decreasing trend of K with the increase of the surface roughness and the K value approaches 57.7 asymptotically. Here, it should be noted that the K values from the correlation of Bai and Gosman (1995) differ from those by Cossali et al. (1997) even though both of them are based on the same experimental results (by Stow and Hadfield, 1981). This seems to be due to a mistake made by Cossali et al. (1997) in adopting the drop characteristic length ; they used the drop

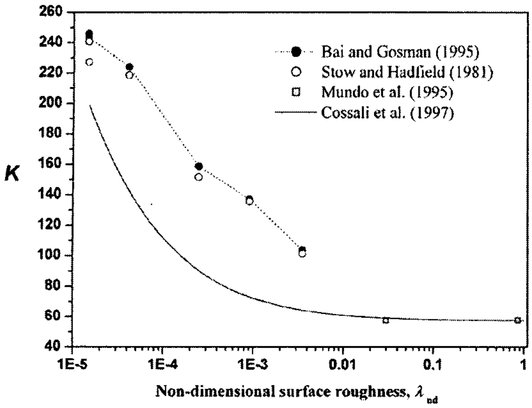

Fig. 4 Comparison between various spread/splash criteria for dry walls

diameter as the characteristic length while the experimental results are based on the drop radius. Therefore, the Cossali et al.'s generalized correlation (Eq. (7)) should be modified appropriately to fit the experimental results.

A criterion for splash in flattening (and solidification) of a thermal spray particle has been proposed by Fukumoto et al. (2002) as Eq. (8) in Table 1. The splashing parameter K_f that is another modification of the Sommerfeld parameter was defined. Here, a denotes the ratio of the flattening velocity to the impact velocity of the particle, which is a function of both substrate temperature and the impact velocity. The criterion E was estimated to be with $K_f \approx 7$, regardless of the splat material, impact velocity and the substrate material.

Other than the correlations introduced in Table 1, there are a number of qualitative investigations regarding the regime transition criteria. For example, Sikalo et al. (2002) examined the drop spread behavior on the surfaces having different wettability. They reported that the wettability effect started to appear even at relatively low Reynolds and Weber numbers. In the high wall-temperature range (i.e., in the transition boiling region, $T_N < T_w < T_{Leid}$, and in the film boiling region, $T_w > T_{Leid}$), according to Ko and Chung (1996), the impinging velocity for occurrence of breakup (considered to be the boundary A) linearly decreases with the increase of the drop diameter that is different from the previous criteria of $We_c \approx$ constant (or $V \sim d^{-1/2}$). This is because as the impinging velocity increases, the spread area of the deformed drop increases and resulting in a much increased heat transfer. Therefore, the physical properties of the drops (especially the surface tension) change and the breakup criterion also changes. The effect of the inclination of the heated surface (from the horizontal direction) on the drop behavior at impingement has been reported by Kang and Lee (2000), covering both the nucleate boiling region and the film boiling region. This work again confirms that impingement regime depends on the magnitude of the normal component of drop velocity (or momentum) to the surface.

2.1.2 Wet-wall impingement

When a large number of drops impinge on a surface, flooding occurs and a thin liquid film is formed. In such a case, the drop behavior becomes completely different from that on a dry surface. According to Bai and Gosman (1995), Stanton and Rutland (1996), and Cossali et al. (1997), nevertheless, when a drop is colliding against an adiabatic wet surface, the stick, rebound, spread and the splash regimes remain to exist, similar to the dry-wall cases. That is, Fig. 3 (for dry walls) with their temperature lower than T_B (or T_{PA}) is basically valid with the wetted surfaces, but the transition conditions appear to be different. Table 2 with Eqs. (9)-(20) summarizes the criteria of impingement regime for a wetted wall.

Stick-Rebound Boundary (Criterion C): For this boundary, Stanton and Rutland (1996) proposed the condition of $We_c < 5$ (Eq. (9)) based on the previous measurements, while, Bai et al. (2002) proposed $We_c \approx 2$ (Eq. (10)) that is about the half value. However, according to the earlier work by Bai and Gosman (1995), the stick regime occurs at very low impact energy ($We_c < 1$), and it may be not irrational to understand that the transition occur in the Weber number below 5.

Rebound-Spread Boundary (Criterion D): Bai and Gosman (1995) proposed the $We_c \approx 5$ for the criterion D (Eq. (11)). On the other hand, Stanton and Rutland (1996) proposed somewhat larger value (within the range of $We_c=5\sim10$, Eq. (12)) as the transition criterion. Recently, for the multiple drop impact on liquid layer, Bai and Gosman (2002) proposed the criterion as $We_c\approx 20$ (Eq. (13)) that is about four-fold compared to their original result on the wet collision ($We_c\approx 5$, Eq. (11)), taking account of the neighboring effect of drops. In other words, when the drops are striking the liquid film, they may encounter pre-existing craters and less work is required to form new craters; thereby, the drop bounce occurs even at higher Weber numbers.

In the above works, the transition between the rebound and the spread regimes is simply expressed as the constant values of the critical Weber number. However, Sikalo et al. (2005) later showed that the critical Weber number depended also on the drop size and the liquid properties. They

Table 2 Criteria of impingement regimes for wetted walls

Boundary	Reference	Criterion	Remarks
C (Stick/Rebound)	Stanton and Rutland (1996)	$We_c<5$ (9)	- Drop : water - Liquid layer : water - $60<d<150$ μm
	Bai et al. (2002)	$We_c\approx 2$ (10)	—
D (Rebound/Spread)	Bai and Gosman (1995)	$We_c\approx 5$ (11)	- Drop : water - Liquid layer : deep water
	Stanton and Rutland (1996)	$5<We_c<10$ (12)	- Drop : water - Liquid layer : deep water - $d=2.8$ mm
	Bai et al. (2002)	$We_c\approx 20$ (13)	Neighboring effect of drops considered
E (Spread/Splash)	Naber and Farrell (1993)	$We_c=130$ (14)	- Drop : water, acetone etc. - Liquid layer : water, acetone etc. - $d=3.4$ mm
	Bai and Gosman (1995)	$We_c=1320\cdot La^{-0.18}$ (15)	Wetted surface is assumed to behave as a very rough dry wall.
	Stanton and Rutland (1996) Yarin and Weiss (1995)	$We_c=18.0^2 d\,(\rho_l/\sigma)^{1/2}\nu^{1/4}f^{3/4}$ (16) $f\ (=V_{b,n}/d)$	- Drop : water, glycerol etc. - Liquid layer : water, glycerol etc. - $70<d<340$ μm
	Cossali et al. (1997)	$K'=2100+5880\cdot\delta_{nd}^{1.44}$ (17) $\delta_{nd}(=\delta/d)$ $(0.1<\delta_{nd}<1.0)$	- Drop : water-glycerol mixture - Liquid layer : water-glycerol mixture - $d=3.07$ mm, $\lambda_{nd}\approx 5\times10^{-5}$
	Wang et al. (2002)	$We_c=450$ (18) $(\delta_{nd}\leq 0.1)$	- Drop and liquid layer : 70% glycerol water solution
		$We_c=1375.7\delta_{nd}+340$ (19) $(0.1<\delta_{nd}\leq 1.0)$	
		$We_c=1043.8+232.6\delta_{nd}^{-1}-1094.4\delta_{nd}^{-2}+1576.4\delta_{nd}^{-3}$ (20) $(1.0<\delta_{nd})$	

checked if a constant value of the Sommerfeld number (K) that includes the liquid viscosity effect is enough to represent the criterion D, but this turned out to be not successful. Thus, a generalized dimensionless correlation for the spread-rebound criterion is not available yet.

Spread-Splash Boundary (Criterion E): There are number of works performed on the transition criterion between the splash and spread regimes: Naber and Farrell (1993), Bai and Gosman (1995), Stanton and Rutland (1996), Yarin and Weiss (1995), Cossali et al. (1997), and Wang et al. (2002). As a part of the spray-wall impingement study on DI-type engine fuel spray, Naber and Farrell (1993) observed that the splash occurs when the Weber number exceeds 130 as Eq. (14) in Table 2. However, Bai and Gosman (1995) proposed to use Eq. (15) that is basically the same with Eq. (5) for a dry wall with a high roughness ($\bar{\lambda}=12$ in Table 1), where the wetted surface was assumed similar to the rough surface. Effect of the drop-wall collision frequency for a train of drops has been taken into account in Eq. (16) by Stanton and Rutland (1996), based on the measurement of Yarin and Weiss (1995). Dependence of the criterion E on the thickness of the liquid film (or layer) was studied, and Eq. (17) was proposed by Cossali et al. (1997) as a function of non-dimensional thickness ($\delta_{nd}=\delta/d$). Recently, Wang et al. (2002) proposed different criteria for the splash-spread boundary according to the non-dimensional film thickness (δ_{nd}) as Eqs. (18) ~ (20), and these are depicted in Fig. 5. The critical Weber number increases with increasing of δ_{nd} for thin liquid films while decreases and approaches a constant value for thick liquid films. In the same figure, the correlation of Cossali et al. (1997) was also plotted for different values of the Ohnesorge number to represent the effect of the liquid properties for the film thickness range of $\delta_{nd}=0.1-1.0$. The increasing trend of the Cossali et al.'s correlation coincides with the trend of Wang et al. (2002) for the film thickness range of $\delta_{nd}=0.1-1.0$, and well matches when Oh=0.0316. In general, within the range of $\delta_{nd}=0.1-1.0$, the Cossali et al.'s correlation (1997) shows more generality, while the result of Wang et al. (2002) covers wider range of the liquid film thickness. One thing to note is on four different thickness regimes (Eqs. (21)-(24)) for the liquid layer provided by Tropea and Marengo (1999) as listed in Table 3; i.e., thin film, liquid film, shallow pool, and deep pool. The first three regimes (Eqs. (21)-(23)) approximately match with the three thickness ranges of Wang et al. (2002) (Eqs. (18)-(20)), respectively, and the fourth regime (deep pool, Eq. (24)) is considered to be in the thick-film range with an asymptotic value of $We_c \approx 1000$ in Fig. 5.

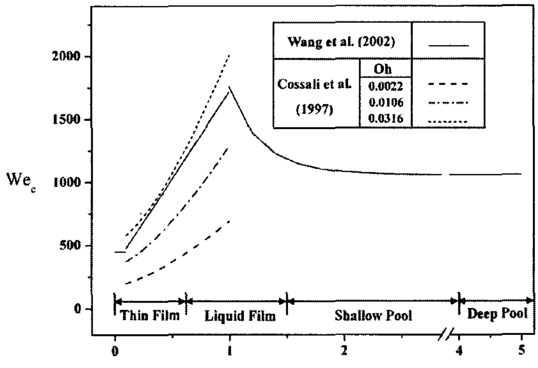

Fig. 5 Comparison between spread/splash criteria for wetted walls

Table 3 Various impact regimes for impact on a wetted surface ($L_{nd}=\bar{L}/d$)-Tropea and Marengo (1999)

Regimes	Ranges		Characteristics
Thin film	$L_{nd}<\delta_{nd}<3\lambda_{nd}^{0.16}$	(21)	Impact depends on surface features, e.g. roughness
Liquid film	$3\lambda_{nd}^{0.16}<\delta_{nd}<1.5$	(22)	Dependence becomes weak
Shallow pool	$1.5<\delta_{nd}<4$	(23)	Impact is independent of surface characteristics but still on film thickness
Deep pool	$\delta_{nd}\gg 4$	(24)	Impact does not depend on film thickness

2.2 Post-impingement characteristics

Most of the studies on the post-impingement behavior of a single drop are for the rebound and splash regimes, where, whole or part of the impinging drop departs from the surface after the impact. In other words, the velocities of the bouncing drops (after the rebound) or sizes, number and velocities of the secondary drops (after the splash) are the items of interest. Table 4 summarizes the post-impingement characteristics of a single drop with the corresponding correlations (Eqs. (25)-(33)).

Regarding the drop bouncing velocity after the impact on a dry wall at room temperature, Bai and Gosman (1995) suggested to use Eq. (25), which was originally developed for a solid particle bouncing on a solid wall by Matsumoto and Saito (1970). Here, the bouncing velocity is expressed in terms of the impinging velocity and the restitution coefficient (e). The same correlation was also adopted by Lee and Ryou (2001) in developing a comprehensive spray-wall prediction model that is going to be introduced later.

For the number of secondary drops after the splash process under the room temperature condition, Bai and Gosman (1995) proposed Eq. (26) in terms of the Weber number only. Later, Yoon and Desjardin (2006) considered the effect of the liquid viscosity by introducing a newly defined Reynolds number, Eq. (28), which includes the surface tension as well as the liquid viscosity and is originated from the wave analysis of the liquid surface. On the other hand, for the splash on the high-temperature walls, Eq. (27) was adopted by Lee and Ryou (2000), based on the experimental results on the drop splashing by Naber and

Table 4 Post-impingement hydrodynamic characteristics

Characteristics	Reference	Correlations	Remarks
Droplet velocity after impact on dry wall (Regime : rebound)	Matsumoto and Saito (1970)	$V_{a,n}=-eV_{b,n},\ V_{a,t}=\frac{5}{7}V_{b,t}$ (25) $e=0.993-1.76\theta_I+1.56\theta_I^2-0.49\theta_I^3$	- Drop : glass & copper beads - d=0.5, 1.0 mm
Number of secondary drops (Regime : splash)	Bai and Gosman (1995)	$N=a_o(\mathrm{We}/\mathrm{We}_c-1),\ a_o\approx 5$ (26)	- Liquid : water - d=2.2, 3.0, 4.0 mm
	Lee and Ryou (2000)	$N=0.187\mathrm{We}_{b,n}-4.45$ (27)	- Liquid : water et al. - $T_{\mathrm{Leid}}<T_W$
	Yoon and Desjardin (2006)	$N=0.1\ \mathrm{Re}_I$ (28) $(\mathrm{Re}_I=V_{b,n}(\pi^2\rho_l d^3/\sigma)^{0.25}/(2\nu^{0.5}))$	- Liquid : water et al. - Substrate : linen sheet
Mass ratio of splashed drops m_{sp}/m_I (Regime : splash)	Bai and Gosman (1995)	$0.2+0.6RN(0,1)$ for a dry wall (29) $0.2+0.9RN(0,1)$ for a wetted wall (30)	- Liquid : water - d=2.2, 3.0, 4.0 mm
	Stanton and Rutland (1996)	$-27.2+3.15u-0.116u^2+1.40\times10^{-3}u^3$ (31) for a wetted wall where, $u=V_{b,n}(\rho_l/\sigma)^{1/4}\nu^{-1/8}f^{-3/8}$	- Liquid : ethanol - $70<d<340\ \mu m$
Splashed drop size distribution (Regime : splash)	Stanton and Rutland (1996)	$pdf(d_l/d)=\left[\frac{b}{\theta_w}\left(\frac{d_l/d}{\theta_w}\right)^{b-1}\right]\exp\left[-\left(\frac{d_l/d}{\theta_w}\right)^{b}\right]$ (32) where, $b=2.71-9.25\times10^{-4}\mathrm{We}$ $\theta_w=0.210-7.69\times10^{-5}\mathrm{We}$	- Weibull distribution b : shape parameter θ_w : scale parameter
	Bai et al. (2002)	$pdf(d_i)=\frac{1}{\bar{d}}\exp\left(-\frac{d_i}{\bar{d}}\right)$ (33) where, $\bar{d}=\frac{\bar{d}_{30}}{6^{1/3}}=\frac{1}{6^{1/3}}\left(\frac{m_{sp}/m_I}{N}\right)^{1/3}d_I$	- chi-squared distribution $\bar{d}$: number mean diameter

Farrell (1993).

As for the mass ratio (m_{sp}/m_I) of the splashed drops, Eqs. (29) and (30) have been introduced by Bai and Gosman (1995), which were deduced from the previous observations for dry walls ($m_{sp}/m_I=0.2-0.8$) and wetted walls ($m_{sp}/m_I=0.2-1.1$), respectively. Here, $RN(0,1)$ denotes a random number between 0 and 1. Later, Stanton and Rutland (1996) suggested Eq. (31), deduced from the measurements of Yarin and Weiss (1995). In this equation, the non-dimensional velocity u includes the effects of drop velocity and liquid properties as well as the impinging frequency. Equation (31) is considered to be an advanced correlation compared to Eqs. (29) and (30) by Bai and Gosman (1995).

Bai and Gosman (1995) assumed in their analysis that the size of the splashed drops is uniform, and determined this value from the number (Eq. (26)) and the mass ratio (Eq. (29) or (30)) of the secondary drops. On the other hand, Stanton and Rutland (1996) proposed Eq. (32), a size distribution function for the splashed drops, based on the measurements of Mundo et al. (1995). In this equation, b and θ_w denote the shape parameter and the scale parameter, respectively. Another functional form of the size distribution has been adopted by Bai and Gosman (2002) in modeling the post-impingement behavior of a spray as Eq. (33) that is based on the measurements of Stow and Steiner (1977), Mundo et al. (1995) and Yarin and Weiss (1995). In this equation, $\bar{d}$ stands for the number mean diameter as defined in Table 4.

The surface roughness, temperature and the liquid viscosity also play important roles in formation of secondary drops. Though a specific correlation form was not provided, Cossali et al. (2005) observed that the liquid viscosity determines the time required for secondary-drop formation while the surface roughness and the wall temperature affect sizes and number of drops after the impact.

A number of basic studies on the phenomenon of heat transfer between an impinging drop and a hot wall have been performed for application to spray cooling, steel rolling, electronics cooling, DI engine combustion, fire suppression, etc. For example, Bolle and Moureau (1982) and Bernardin et al. (1997) showed that the heat transfer rate from a heated surface to a drop can be estimated from the time-variation of the drop-wall contact area, and the corresponding information has been obtained experimentally. Abu-Zaid and Atreya (1994) studied the solid-porosity effect on the transient cooling with droplet evaporation. They reported that time variations of the surface and the in-depth temperatures of the porous solid (wall) is different from those of the non-porous solid due to the water penetration effect.

3. Experimental Observation on Wall Impingement of Sprays

Global behavior of a spray (cloud of drops) in the wall impingement region has been a topic of interest for a long time because the spray-wall impingement phenomena is widely observed in various engineering applications, such as the fuel injection in internal combustion engines and the surface cooling and treatments in material processing. The information to be sought includes the outline shape and the internal structure of the spray flows, and their overall heat transfer performance, as summarized in Table 5.

As illustrated in Fig. 6, the spray outline is characterized by the spray radius (R_s) and the height (H_s), and their time variations can be obtained through the visualization technique. Detailed information on the internal structure of the post-impingement spray flow, represented by the velocities and sizes of the rebound/splashed drops at local points as well as the shape and thickness of the liquid film at the wall, became available by recent development of optical measurement tech-

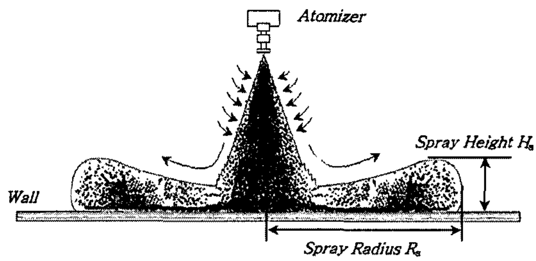

Fig. 6 Impinging spray outline (Spray height and radius)

niques including the phase-Doppler anemometry (PDA).

Katsura et al. (1989) proposed correlations for time variations of spray radius (Eq. (34)) and height (Eq. (35)) in terms of the pressure drop (Δp) and ambient pressure (or density, ρ_{amb}), and also examined time variation of the local drop concentration using the laser light sheet extinction method. Later on, Fujimoto et al. (1990) reported the effect of the wall inclination angle (α_w in Fig. 7) on the spray radius and height; with the higher inclination, the downstream spray radius ($\boldsymbol{R}_{x2}$) and height ($\boldsymbol{H}_{x2}$) increase while the upstream spray radius ($\boldsymbol{R}_{x1}$) and height ($\boldsymbol{H}_{x1}$)

Table 5 Impinging spray outline and internal structure

Measuring Quantities	Remarks	References
Studies on Global Configuration of Impinging Sprays		
Spray radius and height	$R_S=3.87\Delta p^{0.89}\rho_{amb}{}^{-0.24}(t-t_{imp})^{0.48}$ (34) $H_S=1.23\Delta p^{0.52}\rho_{amb}{}^{0.048}(t-t_{imp})^{0.35}$ (35)	Katsura et al. (1989)
	Variable: Impingement angle	Fujimoto et al. (1990) Mathew et al. (2003)
Distribution of droplet density (concentration)	Measuring technique: Laser light extinction method Variables: Injection pressure, Ambient pressure, Wall distance	Katsura et al. (1989)
Studies on Internal Structure of Impinging Spray		
Sizes and velocities of drops	Measuring technique: PDA Variable: Wall temperature	Arcoumanis and Chang (1994), Arcoumanis et al. (1997)
	Measuring technique: PDA	Panao and Moreira (2004)
	Measuring Technique: PDPA Variable: Impingement angle	Mathew et al. (2003)
	Variable: Liquid film	Ghielmetti (2001)
Thickness of deposited fuel film	Measuring Technique: Optical fiber technique	Johnen and Haug (1995)
Shape of deposited fuel film	Measuring Technique: Non-intrusive optical method	Mathew et al. (2003)
Overall Heat Transfer Performance		
Spray heat flux	$\mathrm{Nu}=0.34\frac{\mathrm{We}^{0.94}}{\mathrm{Re}^{0.53}\mathrm{Pr}^{0.33}}$ (36)	Arcoumanis and Chang (1994)
Spray heat transfer *effectiveness*	Spray Weber number $\mathrm{We_s}=\frac{G^2 d}{\rho_l \sigma}$ (37) $\varepsilon=\frac{q''}{G[i_{lv}+c_{p,l}(T_{sat}-T_l)+c_{p,v}(T_w-T_{sat})]}$ (38) $\varepsilon=8\times10^{-7}\cdot[\mathrm{We_s}\cdot T_{sat}/(\Delta T_{sub}+\Delta T_{sat})]^{-0.62}$ $+3.5\times10^{-3}\cdot[\mathrm{We_s}\cdot T_{sat}/(\Delta T_{sub}+\Delta T_{sat})]^{-0.2}$ (39)	Yao and Cox (2002)

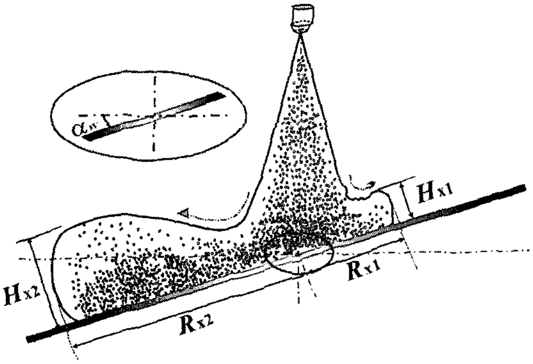

Fig. 7 Influence of impact angle on spray outline (based on Fujimoto et al., 1990)

decrease. Mathew et al. (2003) also examined the effect of the impingement angle (30°, 45° and 60° from the normal direction) on the secondary droplet cloud (spray shape), where the height of the cloud decreased and the spray radius grew faster with the higher impingement angle.

Effects of injection and ambient pressures and distance between the diesel injector and the wall on the drop density (concentration) distribution have been reported by Katsura et al. (1989) As the injection pressure is increased, the drop density decreases due to enhancement of air-fuel mixing. On the other hand, the drop density increases with increasing of the ambient pressure because the spray volume (represented by the radius and the height) decreases and the air-fuel mixing becomes less active. Also, the spray density increases with decreasing of the distance from the injector because of the increase of the adhered fuel ratio.

Arcoumanis and Chang (1994), Arcoumanis et al. (1997) measured size and velocity of drops simultaneously over the spray region using a PDA in order to get internal structure of the diesel spray after the impingement on both the heated (150℃) and the unheated (20℃) walls, thereby the combustion phenomena could be predicted. At the higher wall temperature, the average drop size at the impinging point appeared smaller and the tangential velocities of drops increased. Similar work has been performed later by Panao and Moreira (2004) using the gasoline spray under the room temperature condition to understand basic mechanism of the spray impingement such as formation secondary drops and the liquid film. Mathew et al. (2003) also measured the incoming and secondary drop sizes and velocities of an iso-octane spray using the PDPA technique for various impingement angles. In general, the average drop size increased in the radial direction along the wall because the large drops tend to move further downwards due to the larger momentum compared with the small drops. However, the effect of the impingement angle appeared minor. Another interesting work on the internal structure of a spray after the impingement has been reported by Ghielmetti (2001). There, the size and velocity of drops near the vertical cone-shaped surface were measured along the downstream direction to see the effect of the liquid film thickness deposited on the surface.

Information on the shape and thickness of the liquid film deposited on the surface enables us to predict the mass ratio of sprays that is important in practical design of the spraying systems. Johnen and Haug (1995) developed an optical fiber technique to measure the fuel film thickness at the sprayed surface. Mathew et al. (2003) also measured the film thickness as well as the shape through visualization.

Regarding the heat transfer between the impinging diesel spray and the hot wall, Arcoumanis and Chang (1994) proposed a correlation as Eq. (36) in Table 5 showing an accuracy of ±23%. As for the spray (water) cooling of the high temperature surfaces (above the Leidenfrost temperature), Yao and Cox (2002) proposed a generalized heat transfer correlation that covers most of the previous measurements. They introduced mass flux (G) as a parameter in the spray Weber number (Eq. (37)) to express the spray heat transfer effectiveness (ε, Eq. (38)), and the measured results are well represented by Eq. (39) for a wide range of the spray Weber number ($6\times10^{-10}<We_s<3\times10^{-2}$) within an accuracy of 17%.

4. Modeling of Spray-Wall Interaction

In this part, several works on the modeling of a single, impinging drop are introduced. About a decade ago, Pasandideh-Fard et al.(1996) numerically predicted the behavior of a drop in the regimes of spread and rebound using the SOLA (solution algorithm)-VOF (volume of fluid) method and checked the validity of their model by comparing it with their own measurements. They examined the effect of the surface tension (by changing the concentration of the sodium dodecyl sulphate (SDS) in pure water up to 1000 ppm) on the spread and receding (recoil) of drops, and concluded that the surface tension affects the receding stage while the inertia force mainly governs the spread stage. As an effort to predict the effect of the surface temperature on the time variation of the drop shape, Harvie and Fletcher (2001, 2001a) used the VOF model and reported that their predicted results agree well with the experimental observations. For prediction of the spread phenomenon (including the crown formation and jetting) of an inviscid drop impacting on a liquid film, Davidson (2002) used the techniques of VOF and BIM (boundary integral method), and reported that the radius of the crown increased with the rate of the square root of the dimensionless time ($\tau = (Vt)/(10^3 r_d)$).

Later, Roisman et al.(2002) predicted the hydrodynamic behavior of two adjacent drops impacting on the surface simultaneously, where the interaction between the drops is considered. Such basic models (with a single drop or a couple of drops) should be used as the foundation of the comprehensive models for prediction of the spray-wall impingement behavior. At the same time, Sivakumar and Tropea (2002) reported that the liquid film thickness and velocity are neither uniform (spatially) nor constant (temporally) because of the influence of the previously impinged drops and/or neighboring drops, and such non-uniformity affects the size distribution shape of the secondary drops. Thus there should be a way to predict the local thickness and velocity of the liquid film for accurate modeling of the drop impinging phenomenon.

There have been a number of spray-wall interaction models reported predicting the outline shapes as well as the drop sizes and velocities at the local points, and Table 6 summarizes some of the recent works related to this subject. The models of Naber and Reitz (1988) and Wang and Watkins (1993) underestimate the spray height after the impact. This is because the drop-shattering phenomenon after the impact was neglected and the impingement regime was not specified in their models. (Bai and Gosman, 1995; Mundo et al., 1998) Moreover, the drop size and velocity information at the local points could not be provided properly because of lack of the experimental results for validation of their models until

Table 6 List of spray-wall interaction models

Models	References	Remarks
Prediction of Spray Outline	Naber and Reitz (1988) Wang and Watkins (1993)	Underprediction of Wall Spray Dispersion
Prediction of both Spray Outline and Internal Structure	Park and Watkins (1996)	Liquid Film Deposition Not Considered.
	Mundo et al.(1997, 1998) Lee and Ryou (2000) Bai et al.(2002) Yoon et al.(2006) Yoon and Desjardin (2006)	Liquid Film Deposition Considered.
Prediction of 1. Spray Outline 2. Internal Structure 3. Transient Film Behavior (Film Radius/Thickness and Adhered Liquid Ratio)	Bai and Gosman (1995) Stanton and Rutland (1996, 1998) Lee and Ryou (2001)	

the measured data (using PDA) by Arcoumanis and Chang (1994) were available. Since then, a number of improved models have been proposed to predict both the spray outline and the internal structure as listed in Table 6. Among them, Park and Watkins (1996) did not consider the liquid film deposition on the surface while the models by Mundo et al. (1997; 1998), Stanton and Rutland (1996; 1998), Bai and Gosman (1995), Bai et al. (2002), Lee and Ryou (2000; 2001), Yoon et al. (2006) and Yoon and Desjardin (2006) considered that. In particular, the models of Bai and Gosman (1995), Stanton and Rutland (1996; 1998) and Lee and Ryou (2001) can predict the transient film behavior (such as the adhered liquid ratio and the film radius and thickness) as well as the spray outline and the internal structure.

For comprehensive prediction of the spray-wall impingement phenomenon, the approach made by Lee and Ryou (2001) is shown as an example in Table 7. This model covers the rebound, spread and splash regimes, and predicts the post-impingement characteristics of drops as well as the deposited film radius and thickness.

Another example of the spray-wall impingement model can be found from the work of Bai et al. (2002) This model was developed to predict various aspects of gasoline sprays with larger drops compared to those in high-speed DI engines and with a larger energy dissipation by drop splashing. Regarding the regime transition criteria for the wet-wall impingement, some modifications have been made to their previous work (Bai and Gosman, 1995): As noted earlier, they introduced $We_c \approx 2$ (Eq. (10)) as the new criterion for the boundary C (the stick-rebound bound-

Table 7 An example of comprehensive spray-wall prediction model (Based on Lee and Ryou, 2001)

Characteristics	Sub-Models
Impingement Regime	Rebound → Spread : $We_c=5$ Spread → Splash : $K=57.7$
Post-impingement Characteristics	Droplet Velocity After Rebound $V_{a,n}=eV_{b,n},\ V_{a,t}=\frac{5}{7}V_{b,t}$ $e=0.993-1.96\theta_i+1.56\theta_i^2-0.49\theta_i^3$ Deposited Mass Fraction $0.2+0.9RN(0,\ 1)$ Number of Splashed Droplets $N=0.187We_{b,n}-4.45$ Splashed Droplet Velocity $V_{a,t}=V_{b,t}+V_f\cos\omega$ $V_{a,n}=V_{b,n}+V_f\sin\omega$ where, V_f : film velocity, ω : deflection angle
Film Radius and Thickness	Film Radius $r_f=\sin\phi\sqrt[3]{\frac{3\forall_f}{\pi(2-3\cos\phi+\cos^3\phi)}}$ where, ϕ : curvature radius of film $\forall_f$: volume of film Film Thickness $\delta=m_f/\rho_l\pi r_f^2$ where, m_f : mass of film $=\underbrace{\sum_i\frac{n_i\rho_l\pi d_{b,i}^3}{6}}_{\text{Rebound}}+\underbrace{\sum_i\frac{n_i(1-m_{sp}/m_i)\rho_l\pi d_{b,i}^3}{6}}_{\text{Splash}}$

ary), and $We_c \approx 20$ (Eq. (13)) as the modified criterion for the boundary D (the rebound-spread boundary) that is fourfold compared to Eq. (11) in Table 2. These modifications take account of the interference (neighboring) effects of the previously impinged droplets. For the post impingement characteristics in the splash regime, the original approach of Bai and Gosman (1995) remained the same except for prediction of the secondary drop sizes that were evaluated from a probability density function (Eq. (33)) instead of the uniform probability assumption adopted previously. Besides, the energy balance relationship for splashing drops was modeled more realistically compared to the previous work (Bai and Gosman (1995)). The modified model better predicts the measured data of Arcoumanis et al. (1997) than the previous model of their own (Bai and Gosman (1995)).

To the authors' knowledge, the most recent works on the modeling of spray impingement phenomena have been performed by Yoon and DesJardin (2006) and Yoon et al. (2006). Yoon et al. (2006) constructed a numerical model based on an unsteady Reynolds-averaged Navier-Stokes (RANS) formulation and used a stochastic separated flow (SSF) approach for the droplets. In the following work of Yoon and DesJardin (2006), several linear-theory-based models were compared for prediction of the droplet shattering due to the spray impingement on a flat surface or on a cylindrical surface. They concluded that the viscosity tends to dampen the instability and number of the satellite drops is reduced when the liquid becomes highly viscous.

5. Summary and Conclusion

In this article, various criteria of impingement regimes and the post-impingement characteristics for single drops have been reviewed. Also, recent models for prediction of spray-wall interaction behavior were introduced along with the experimental works to support them. Basically, most of the spray-wall interaction behavior is unveiled, and performance of the prediction models has been greatly improved owing to large progress of numerical techniques and local collision models. However, for the verification purpose and further improvement of the prediction models, there should be more accurate and extensive experimental data on the regime transition criteria, size and velocity of the rebound and splashed drops, and on the behavior of the liquid film deposited on the surface.

Moreover, there are a variety of subjects still to be investigated from the viewpoint of engineering applications, and some of them are listed as follows :

(1) Dependence of heat transfer regime criteria on hydrodynamic behavior of impinging drops

(2) Drop behavior at the surface of porous bodies

(3) Solidification of impinging drops at the wall surface

(4) Hydrodynamic behavior of electrically charged drops for electro-spraying

(5) Boiling/evaporation of the deposited liquid film

(6) Prediction of liquid film behavior on the surface with multiple impingement of drops

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