Impingement of liquid jets at atmospheric and elevated pressures: an observational study using paired water jets or water and methylcyclohexane jets

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We have observed the impingement of two cylindrical liquid jets of either the same liquid, water, or two mutually immiscible liquids, water and methylcyclohexane (MCH), in either air under normal pressure (0.101 MPa) or nitrogen gas under elevated pressures up to 4.0 MPa. The flow rates of the two jets were adjusted such that they had equal axial momentum. Irrespective of the system pressure, we distinguished two characteristic regimes: the lower flow-rate regime, in which the jet impingement formed a regularly shaped planar sheet, and a higher flow-rate regime, in which a wrinkled sheet repeated azimuthal breakup. The transition from the former to the latter regime occurred at a lower flow rate for the water–MCH impingement than for the water–water impingement. An increase in the system pressure tended to shrink the liquid sheets, to promote the transition to the sheet-breakup regime and to intensify the liquid atomization. The formation of water–MCH compound droplets by the water–MCH impingement was confirmed visually.

Keywords: impinging jets; liquid sheet; compound droplets; atomization

1. Introduction

When two cylindrical coplanar liquid jets collide in a gas phase, they form an expanding liquid sheet perpendicular to the plane on which the jet axes lie. Droplets are ejected into the gas phase either directly from the rim of the sheet or from the ligaments intermittently detached from the sheet. Owing to this good liquid atomization, such jet-on-jet impinging devices have been applied to propellant injectors for bipropellant rocket engines (Rupe 1953; Heidmann et al. 1957; Foster & Heidmann 1960; Anderson et al. 1995) and to reactors for various chemical engineering processes, including liquid–liquid extraction, absorption and desorption of gases, drying of solids, crystallization and precipitation, and so on (Kudra & Mujumdar 1989; Berman & Tamir 2000; Sainen et al. 2006). Recently, we proposed using a jet-on-jet impinging operation
for forming clathrate hydrates from, for example, natural gas for its storage and transport or biogases for separating undesirable (toxic or incombustible) species, such as hydrogen sulphide and carbon dioxide, thereby making them sufficiently methane rich (Murakami et al. 2009). If two water jets were forced to collide in, for example, natural gas under a pressure of approximately 4 MPa and at a temperature of approximately 2°C, a hydrate of structure II could form on water droplets sprinkled in the gas phase. One of the two water jets may be replaced by a jet of hydrophobic liquid having a significantly low freezing point. If pre-cooled much below the water freezing point, the hydrophobic liquid possibly functions as a coolant for removing the heat released by the hydrate formation. Moreover, the liquid may also serve, with the help of the surrounding hydrate-forming gas, as a companion hydrate guest, if it is one of the large-molecule guest substances whose molecules may fit into $5^{12}6^8$ cages of the structure-H hydrates. In a previous study (Murakami et al. 2009), we succeeded in forming a structure-H hydrate using water and methylcyclohexane (MCH) jets impinging on each other at an angle of $2\theta = 120^\circ$ (figure 1) in a methane atmosphere pressurized up to 3.7 MPa. We observed an elliptic liquid sheet radially extending, though being shifted downwards, from the point of the jet collision. The sheet tended to shrink, more violently ejecting droplets from its periphery, with an increase in the pressure. It should be noted, however, that, in the above study, priority was given to demonstrate hydrate formation by the jet-on-jet impinging operation over the fluid-mechanical investigation of the impingement of immiscible liquid jets at elevated pressures. The experimental system used there was not necessarily suitable for fine fluid-mechanical studies; that is, the jets issuing from simply drilled orifices were significantly disturbed, and the water and MCH flows to the orifices were accompanied by weak pulsations originating from plunger pumps used for circulating these liquids through a hydrate-forming chamber. We thus intended to observe in this study...
the impingement of fluid-mechanically well-defined jets of either the same liquid, water, or two mutually immiscible liquids, water and MCH, in a gas phase pressurized up to 4.0 MPa.

Besides application-oriented studies, such as those cited earlier, a number of fine fluid-mechanical studies have been performed to explore the nature of formation and disintegration of geometrically beautiful liquid sheets resulting from the oblique or coaxial collision of equal cylindrical jets and/or to investigate the characteristics of liquid atomization available by such collisions (see Dombrowski & Fraser 1954; Taylor 1960; Dombrowski & Hooper 1962, 1963; Huang 1970; Ibrahim & Przekwas 1991; Anderson et al. 1992; Kang et al. 1995; Ryan et al. 1995; Shen & Poulikakos 1998; Choo & Kang 2001, 2002; Bush & Hasha 2004; Bremond & Villermaux 2006; Li & Ashgriz 2006; Ibrahim & Outland 2008; Lee et al. 2009). Most of these studies dealt with the impingement in air under atmospheric pressure (approx. 0.10 MPa). In principle, the ambient pressure affects the density of air or, more generally, the gas phase in which liquid sheets are brought into contact, which, in turn, may affect the occurrence of the Kelvin–Helmholtz instability on liquid sheets. Only Dombrowski & Hooper (1962) observed sheet-disintegration and atomization behaviour over a wide range of ambient pressures, i.e. from a vacuum condition (approx. 6.5 kPa absolute) to 2.17 MPa. They reported that a substantial pressure dependence was recognized only when the pressure was elevated above atmospheric pressure because of the increasing effect of the aerodynamic force exerted on liquid sheets. However, their observations were limited to a fully turbulent jet-flow regime in which the Reynolds number, $Re_j$, defined as $V_j D/\nu$, ranged from $8.7 \times 10^3$ to $19.9 \times 10^3$, and hence the liquid sheets formed by jet collision were substantially ruffled, each being subjected to nearly periodical disintegration over its circumference, irrespective of the ambient pressure; where $V_j$, $D$ and $\nu$ denote the axial liquid velocity at the nozzle outlet, the inside diameter of the nozzle outlet and the kinematic viscosity of the liquid, respectively. Fukui & Sato (1972) reported that no effect of ambient pressure increase from 0.1 to 0.25 MPa was detected on the size of the circular liquid sheets formed by coaxial jet collision over $Re_j$ ranging from 690 to 1220, wherein the sheets were laminar and free from any visible waves on their surfaces. Obviously, the pressure effect on the formation and disintegration of liquid sheets over a wide liquid-flow-rate range covering both the smooth-sheet and ruffled-sheet regimes has not yet been revealed. Besides, none of the fluid-mechanical studies found in the literature dealt with the impingement of two immiscible liquid jets, even under atmospheric pressure conditions. The only previous study dealing with the impingement of two immiscible liquid jets is found in an early technical report by Rupe (1953), who observed the impingement of water and carbon tetrachloride jets, in addition to that of two water jets, in air at atmospheric pressure. Rupe’s attention was focused on the point of how the liquids injected from the two nozzles were spatially mixed as a result of atomization caused by jet impingement. He hardly described his visual observation of liquid sheets formed by the impingement of two immiscible jets. Based on the literature survey as outlined earlier, we expect that our present study, dealing with both water-to-water and water-to-MCH impingements at both atmospheric and elevated pressures, can contribute to our understanding of the mechanics of liquid-jet impingement and to our insight into its engineering applications, including clathrate-hydrate-forming operations.
2. Description of experiments

(a) Experimental apparatus

The nozzle layout that we used to observe the liquid-jet impingement is schematically illustrated in figure 1. Two tubular nozzles identical to each other were symmetrically arranged on the same vertical plane. This layout is geometrically characterized by \( \theta \), the inclination angle of each nozzle from the vertical, and \( l \), the distance between each nozzle tip and the point at which the two nozzle axes meet, which are specified later in this section. We constructed two experimental setups in this study: one for experiments at atmospheric pressure and the other for experiments at elevated pressures. They are schematically illustrated in figure 2 and described below.

Either setup was centred by a twin-nozzle assembly for generating hydrodynamically well-controlled jets in such a way as to enable them to accurately collide on the vertical axis of symmetry of the twin-nozzle arrangement. Each nozzle had a 0.5 mm inside diameter and 200 mm length, so that the internal liquid flow could be fully developed at its tip, which was cut at right angles to the axis to ensure the formation of an axially symmetric jet flow beyond the tip. The upstream end of each nozzle was connected to a 3785 cm\(^3\) stainless-steel cylinder used as a liquid (water or MCH) reservoir, in which the liquid was pressurized by pressure-regulated nitrogen gas to be expelled through the nozzle at a prescribed flow rate. The flow rate was controlled by a metering valve (Swagelok SS-SS4) and measured by an oval-gear-type positive displacement flowmeter (B.I.O-Tech VZS-005-VA) coupled with a digital indicator (Japan Startechno ES2150).

The nozzle assembly for the atmospheric pressure experiments was composed of two nozzles made of Pyrex precision-bore capillaries and their holders. Each holder was mounted on a precision rotary stage, which was in turn mounted on a two-axis stage, that allowed us to precisely control the position and orientation of each nozzle over a wide range of inclination angles \( \theta \). The axial distance \( l \) between the tip of each nozzle and the point of jet collision was adjusted at 10 mm throughout the experiment. The above assembly was set in a rectangular open-top vessel made of transparent poly(methyl methacrylate) plates (figure 2a).

Nozzles for elevated pressure experiments were made of stainless-steel tubes. They were inserted in a high-pressure chamber through its top portion, forming a fixed angle of \( 2\theta = 120^\circ \) between their axes (figure 2b) and adjusting the axial distance \( l \) at 10 mm. This chamber was machined from a stainless-steel block into the form of a horizontally oriented stainless-steel cylinder with an inside diameter of 200 mm and an inside length of 410 mm. Both ends of the cylinder were closed with flange-type lids, each having a circular sight window, the centre of which was located at nearly the same height as that of the position of the jet collision. The chamber had several ports on its top, which were used for inserting a digital pressure gauge (Valcom VPMC-D-A) and a Pt-wire resistance thermometer into the chamber, supplying nitrogen gas into the chamber to increase the inside pressure to a prescribed level, and discharging the gas. A mechanical device for minutely adjusting the position of one of the two nozzles relative to the other was installed inside the chamber (not illustrated in figure 2b) to enable geometrically right collisions of the two jets.
Impingement of two liquid jets

For recording snapshot images of jet impingement, we used a digital single-lens reflex camera (Canon EOS-20D), on which a zoom lens (Canon EFS 18–55 mm f/3.5–5.6 II USM) or, for measuring the size of dispersed droplets,
Table 1. Properties of test liquids at 0.101 MPa and 25°C.

<table>
<thead>
<tr>
<th></th>
<th>density, $\rho$ (kg m$^{-3}$)</th>
<th>viscosity, $\mu$ (mPa s)</th>
<th>surface tension, $\sigma$ (mN m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>998.9$^a$</td>
<td>1.085$^a$</td>
<td>73.21$^a$</td>
</tr>
<tr>
<td>MCH</td>
<td>770.0$^b$</td>
<td>0.720$^b$</td>
<td>23.85$^b$</td>
</tr>
</tbody>
</table>

$^a$Cited from Wagner & Prüß (2002).
$^b$Cited from TRC Thermodynamic Tables (1999).

A macro lens (Canon MP-E 65 mm f/2.8 1–5x Macro Photo) was mounted, a strobeoscope (Sugawara MSX-1D) adjusted at a 300 r.p.m. flashing frequency and placed opposite to the camera, and a thin Teflon sheet placed in front of the strobeoscope as a light diffuser. For high-speed recording of impingement, the above camera, lens and light source were replaced by a high-speed video camera (NAC Memrecam fx K4 model V-169 or Memrecam GX-1), a 60 mm macro lens (NAC Macro 500) and a 250 W metal-halide fibre-optic illuminator (NAC UF3250NAC), respectively.

All of the entire experimental setup was placed in a laboratory and temperature controlled at 25 ± 1°C. No direct temperature control of any portion of the setup was made. The temperature monitored by the thermometer inserted in the high-pressure test chamber (figure 2b) never deviated from 25 ± 1°C during each experimental operation.

(b) Materials and procedure

The test liquids used in this study were water, which was deionized and distilled in our laboratory, and MCH of the Sigma–Aldrich ReagentPlus grade (99% certified purity). The literature data of properties of water and MCH possibly relevant to this study are summarized in table 1. In the experiments using two water jets, the flow rates through the two nozzles were equalized to each other so that the liquid sheet formed around the point of jet collision was flat and vertical. In the experiments using MCH together with water, their flow rates were independently controlled such that they satisfied the following condition, and hence the two jets had equal axial momentum values at the nozzle outlets,

$$\frac{\dot{V}_{\text{MCH}}}{\dot{V}_w} = \left(\frac{\rho_w}{\rho_{\text{MCH}}}\right)^{1/2},$$

where $\dot{V}$ and $\rho$ denote the volume flow rate and density of the liquid, respectively, and the subscripts ‘w’ and ‘MCH’ denote water and MCH, respectively. It was visually confirmed that a vertically oriented flat sheet was formed around the point of jet collision when the above flow-rate condition was satisfied. Images of such liquid sheets obtained with a horizontal camera axis (figure 2) were captured in a computer and, for determining the size of the sheets, analysed using an image viewer ViX (http://www.katch.ne.jp/~k_okada/index_e.htm). The images of droplets disintegrated from the sheets were captured in the same way and analysed using commercially available software (PARTICLE ANALYSIS v. 3.0 provided by Sumitomo Metal Technology Inc.).

3. Results and discussion

(a) Jet impingement at atmospheric pressure

All the experimental results shown in this section were exclusively obtained using the setup illustrated in figure 2a, in which two liquid jets impinge on each other in an air atmosphere under normal pressure (0.101 MPa). In order to provide the readers with a general view of the variation in the jet-impingement behaviour depending on the liquid flow rate and on the angle of impingement, we display typical snapshots of the impingement of two water jets in figure 3. This figure shows that at each angle of jet collision, the sheet expanding from the point of collision tends to grow with an increase in $\dot{V}_w$, the water flow rate through each nozzle, up to a certain critical flow rate $\dot{V}_{w,cr}$. In this flow-rate regime, the sheet is flat, except for minute transverse waves travelling outward from the point of jet collision, and exhibits an almost steady and regular configuration once $\dot{V}_w$ is fixed. Droplets are generated at, and ejected from, the rim of the sheet into the surrounding air, being only slightly scattered along the horizontal axis normal to the sheet. With a further increase in $\dot{V}_w$ beyond the critical flow rate $\dot{V}_{w,cr}$, the sheet drastically shrinks as a result of a nearly periodic disintegration of its entire periphery into the form of discrete ligaments. Droplets are mostly formed by the disintegration of such ligaments. The critical flow rate $\dot{V}_{w,cr}$ separating the ‘steady-sheet regime’ and the ‘intermittent sheet-breakup regime’ tends to increase with an increase in the angle of jet collision $2\theta$ from 60° to 120°. Our qualitative observations of the jet impingement as outlined earlier are generally consistent with those described, though not necessarily thoroughly, by previous researchers (Dombrowski & Fraser 1954; Heidmann et al. 1957; Dombrowski & Hooper 1963; Huang 1970; Anderson et al. 1995; Bush & Hasha 2004; Bremond & Villermaux 2006; Li & Ashgriz 2006).

Our experiments with water and MCH jets revealed that the impingement of these mutually immiscible jets also exhibits the formation and disruption of liquid sheets, which are apparently similar to those observed with two equal water jets. This fact indicated that such sheets are mostly dual films, each composed of a water layer and an MCH layer. In order to confirm the existence of such composite sheets and to know how they break, we performed some experiments using water coloured with a dye. Figure 4 exemplifies two snapshots obtained in the intermittent sheet-breakup regime. Each snapshot shows that a glaucous water layer ruptured at some locations on the sheet, thereby leaving colourless patches wherein an MCH layer was exposed. The residual area on the sheet, as well as most of the ligaments and droplets dispersed from the rim of the sheets, exhibited a glaucous colour, indicating the presence of water there. Based on these observations, we can draw the following conclusions:

— the impingement of the water and MCH jets forms a sheet composed of a water layer and an MCH layer,
— such a two-layer structure of the sheet may extend to its rim, where it disintegrates into droplets or ligaments, each possibly containing both water and MCH phases, and
— alternatively, the water layer may break at some locations over the sheet, leaving patch-like pits backed with an MCH layer.
Figure 3. Variation in the size, shape and breakup behaviour of the liquid sheet formed by the impingement of two equal water jets in normal-pressure air (0.10 MPa) with the water flow rate, $\dot{V}_w$, through each nozzle and with the angle $\theta$ formed by the two nozzle axes. The aligned pictures were taken with the horizontal camera axis lying on the vertical plane containing the nozzle axes with the aid of stroboscopic backlighting. Scale bar, 10 mm.
Impingement of two liquid jets

Figure 4. Breakup of a dual-layer sheet formed by the impingement of water (containing 0.12 mass% malachite green G (C$_{27}$H$_{34}$N$_{2}$O$_{4}$S)) and MCH jets in normal-pressure air (0.10 MPa), $\theta = 120^\circ$. $\dot{V}_w = 50$ cm$^3$ min$^{-1}$ ($Re_{j,w} = 2385$). Note that the glaucous water layer was occasionally broken, prior to the entire sheet collapse, over some portions of the sheet, thereby leaving a colourless MCH single-layer sheet. Scale bar, 5 mm.

The rupture of the water layer is reasonably ascribed to its inherent instability while it is in back-to-back contact with an MCH layer. Note that the spreading coefficient of water on the MCH–air interface has a large negative value, as indicated by the surface tension data given in Table 1. This means that once the water layer breaks, forming a pit enclosed by a three-phase (water + MCH + air) contact line, a strong imbalance force should be exerted on the line such that the water layer is forced to recede, thereby allowing the pit to grow further.

The shape and size of liquid sheets formed around the point of jet collision have been a matter of research interest (Heidmann et al. 1957; Taylor 1960; Huang 1970; Fukui & Sato 1972; Ibrahim & Przekwas 1991; Anderson et al. 1992, 1995; Kang et al. 1995; Ryan et al. 1995; Bush & Hasha 2004; Bremond & Villermaux 2006; Li & Ashgriz 2006; Ibrahim & Outland 2008). The vertical length $L$ from the point of collision to the downstream tip and the maximum width $W$ of each sheet (Figure 1) were measured in some of the previous studies (Heidmann et al. 1957; Huang 1970; Fukui & Sato 1972; Anderson et al. 1992, 1995; Kang et al. 1995; Ryan et al. 1995; Li & Ashgriz 2006) using two equal jets of water or an aqueous glycerol solution, and were correlated with some jet-flow-characterizing parameters such as the jet velocity $U_j$ or the jet Weber number $We_j$, defined as $We_j \equiv \rho U_j^2 D / \sigma$, where $U_j$, $D$ and $\sigma$ denote the axial flow velocity averaged over the cross section of the outlet of each nozzle (or orifice), the diameter of the outlet of the nozzle and the surface tension of the jet-forming liquid, respectively. (In the
Figure 5. Evolution of the sheet size with the increasing water flow rate $\dot{V}_w$ or the water-jet Reynolds number $Re_{j,w}$. All data were obtained in the 0.10 MPa air atmosphere. The left-hand graphs indicate the vertical sheet length (the distance measured from the point of jet collision to the bottom of the sheet) $L$ and the sheet width (the horizontal distance between leftmost and rightmost tips of the sheet) $W$ relevant to the impingement of two water jets. The right-hand graphs indicate those relevant to the impingement of the water and MCH jets. Each point plotted here represents the mean of the data obtained from 20 snapshots taken at approximately 20 s intervals, and the error bar laid on the point indicates the standard deviation of the data. Note that many of the error bars, particularly those in the steady-sheet regime, are so short that they are completely masked by the closed data marks (for $2\theta = 60^\circ$ (filled circles) and $120^\circ$ (filled triangles)). The longer error bars at the higher flow rates represent large-amplitude fluctuations in $L$ and $W$ due to the intermittent sheet breakup. Open circles, $2\theta = 90^\circ$.

case of impingement of coaxial jets forming a circular sheet (Huang 1970; Fukui & Sato 1972), its radius may be considered to be the length $L$). More specifically, Huang (1970) and Li & Ashgriz (2006) performed such measurements in relatively wide ranges, each extending from the steady-sheet regime to the intermittent sheet-breakup regime. We obtained a set of paired data on $L$ and $W$ for each sheet formed by the impingement of equal water jets or that of the water and MCH jets. These data are plotted in figure 5 in terms of $L$ and $W$ versus the water flow rate $\dot{V}_w$ or the water-jet Reynolds number, $Re_{j,w}$, defined as

$$Re_{j,w} \equiv \frac{\rho_w U_{j,w} D}{\mu_w} = \left( \frac{4}{\pi} \right) \frac{\rho_w \dot{V}_w}{(D\mu_w)},$$

where $U_{j,w}$ and $\mu_w$ denote $U_j$ for the water jet and the viscosity of water, respectively. The data for the impingement of two water jets are replotted in figure 6 in the form of $L/R$ and $W/R$ versus $W_{e_{j,w}}$, the Weber number for the water jet, such that we can directly compare these data with those graphically presented in the papers by Huang (1970) and Li & Ashgriz (2006), where $R$ denotes the radius of the nozzle outlet, i.e. $D/2$. We discuss below some features of the datasets shown in figures 5 and 6.

Figure 5 graphically demonstrates how the flow-rate dependence of the sheet size, as measured in terms of $L$ or $W$, drastically changes as the flow rate $\dot{V}_w$ exceeds $\dot{V}_{w,cr}$, which borders the steady-sheet regime and the intermittent sheet-breakup regime. This change occurs in common in both water–water and water–MCH systems, although the change in the latter system is apparently less drastic, compared with that in the former system, because of the less extensive growth of sheets with the increasing flow rate in the steady-sheet regime. The water-jet Reynolds number corresponding to the border between the two regimes, i.e. $Re_{j,w,cr} = (4/\pi) \rho_w \dot{V}_{w,cr} / (D \mu_w)$, for the water–water system falls in the range from 3100 to 3400. This fact indicates that the transition between the two regimes does not necessarily coincide with the laminar-to-turbulent transition of the water jets. The critical water-jet Reynolds number, $Re_{j,w,cr}$, for the water–MCH system falls in a somewhat lower range, i.e. from 2400 to 2600. It should be noted, however, that the Reynolds number for the MCH jet is defined as
Table 2. Critical conditions at the upper border of the steady-sheet regime (presumably corresponding to the closed-rim regime due to Li & Ashgriz (2006)): comparison between this study and that by Li & Ashgriz (2006). Nozzle diameter $2R$ was 0.5 mm in this study and 0.4 mm in the study by Li & Ashgriz (2006).

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>$We_{j,w,cr}$</th>
<th>$(L/R)_{cr}$</th>
<th>$(W/R)_{cr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>this study</td>
<td>Li &amp; Ashgriz</td>
<td>this study</td>
</tr>
<tr>
<td>60°</td>
<td>210–245</td>
<td>200</td>
<td>66</td>
</tr>
<tr>
<td>90°</td>
<td>210–245</td>
<td>165</td>
<td>100</td>
</tr>
<tr>
<td>120°</td>
<td>245–280</td>
<td>150</td>
<td>117</td>
</tr>
</tbody>
</table>

$Re_{j,MCH} \equiv (4/\pi) \rho_{MCH} \dot{V}_{MCH}/(D \mu_{MCH})$ and related, with the aid of equation (2.1), to the water-jet Reynolds number $Re_{j,w}$ as

$$\frac{Re_{j,MCH}}{Re_{j,w}} = \frac{\mu_w}{\mu_{MCH}} \left( \frac{\rho_{MCH}}{\rho_w} \right)^{1/2}, \quad (3.1)$$

where $\mu_{MCH}$ denotes the viscosity of MCH, i.e. the Reynolds number for the MCH jet is about 1.32 times the Reynolds number for the water jet. Thus, the range of the critical MCH-jet Reynolds number, $Re_{j,MCH,cr}$, bordering the two regimes in the water–MCH system almost matches that of $Re_{j,w,cr}$ for the water–water system.

In figure 6, we can recognize some qualitative differences between our data and those of Huang (1970) and Li & Ashgriz (2006). Our data show remarkable drops in both $L/R$ and $W/R$ as $We_{j,w}$ crosses the border between the steady-sheet and intermittent sheet-breakup regimes, whereas those of Huang (1970) and Li & Ashgriz (2006) exhibit a continuous, though rather sharp, change in $L/R$ from an upward slope to a downward slope at the border. Our data for each of the three jet-collision angles, $\theta = 60^\circ, 90^\circ$ and $120^\circ$, could be quantitatively compared with those of Li & Ashgriz (2006) for the same angle. We compare in table 2 typical data characterizing the border between the two regimes obtained in this study with the corresponding data given by Li & Ashgriz (2006). (Here, we assume that the ‘closed-rim regime’ and the ‘open-rim regime’ defined by Li and Ashgriz correspond to the steady-sheet regime and the intermittent sheet-breakup regime, respectively, because no open-rim sheet was observed in the steady-sheet regime in our experiments under atmospheric pressure. This was not the case in the experiments at elevated pressures, as described later.) Obviously, our data show at every jet-collision angle, a critical water-jet Weber number $We_{j,w,cr} \equiv (4/\pi)^2 \rho_w \dot{V}_{w,cr}^2/(D^3 \sigma_w)$ higher than that of Li and Ashgriz. Furthermore, the dependence $We_{j,w,cr}$ on the jet-collision angle observed in this study is opposite to that reported by Li and Ashgriz. The peak values of $L/R$ and $W/R$ at the regime border observed at $\theta = 120^\circ$ in this study are substantially higher than those reported by Li and Ashgriz. However, this is not the case at smaller angles ($60^\circ$ and $90^\circ$). We cannot provide a clear interpretation for such differences in the experimental results between the two studies. Minute differences in the nozzle size ($D = 0.5$ mm in this study and $0.4$ mm in the study of Li and Ashgriz),
the machining and assembling of the nozzles and related accessories, and the precision in adjusting the two nozzles could possibly be the sources of the above-discussed differences.

As observed in figures 5 or 6, $L$ and $W$ varied only slightly with $\dot{V}_w$ (or $Re_{j,w}$ or $We_{j,w}$) in the intermittent sheet-breakup regime, which is in qualitative agreement with the observations by Anderson et al. (1992, 1995) and Ryan et al. (1995). Such an approximate invariability of the sheet size in this regime should be ascribable to the balance between the expanding flow in the sheet and the quasi-periodic disintegration of the sheet over its entire periphery, both being intensified with an increase in $\dot{V}_w$. For a better understanding of the process of such disintegration and the statistical nature of its occurrence, we have inspected records of high-speed videography. Figure 7 shows two sequences, one for the water–water impingement and the other for the water–MCH impingement, of sheet breakups at flow rates slightly beyond the border between the two regimes. In either sequence, a local rupture of the sheet occurred first at a location above the point of the jet collision, then azimuthally propagated, tearing off a peripheral portion of the sheet from its circular core around the point of the jet collision, thereby resulting in a circumferential breakup of the sheet. Such breakups were repeated at approximately regular intervals. In figure 8, we show such intervals $\tau_b$ and the frequency $f_b$ of the sheet breakups and also $\dot{V}_w\tau_b$, the volume of water supplied through each nozzle during each interval, determined from the records of the high-speed videography. It should be noted that despite a monotonic decrease in $\tau_b$ with an increase in $\dot{V}_w$ (or the water-jet velocity $U_{j,w}$), $\dot{V}_w\tau_b$ hardly changes with $\dot{V}_w$. This means that if the sheet thickness is almost independent of $\dot{V}_w$ or $U_{j,w}$, as indicated in previous studies (Taylor 1960; Ibrahim & Przekwas 1991; Shen & Poulikakos 1998; Choo & Kang 2001), the radial displacement of the sheet periphery in each interval should be almost independent of $\dot{V}_w$ or $U_{j,w}$. This consequence is consistent with our observation that $L$ and $W$ varied no more than slightly with $\dot{V}_w$ in the intermittent sheet-breakup regime. However, the above consequence needs more careful experiment-based examinations in the future because the experimental evidence for the approximate independency of the sheet thickness of $U_{j,w}$ now available (Shen & Poulikakos 1998; Choo & Kang 2001) is limited to the smooth sheets formed in the steady-sheet regime.

(b) Jet impingement at elevated pressures

All the experimental results shown in this section were exclusively obtained with the setup illustrated in figure 2b, in which two liquid jets were impinged on each other at a fixed angle, $2\theta = 120^\circ$, in a nitrogen-gas atmosphere controlled at a pressure ranging from 1.1 to 4.0 MPa or in an air atmosphere at normal pressure, 0.101 MPa. Experiments with the normal-pressure air were performed to confirm, if any, the difference in the sheet-formation/breakup behaviour available with the above setup for higher pressure use from that available with the other setup (figure 2a) for normal-pressure use.

The two sets of pictures arranged in figure 9 demonstrate how the configuration and breakup behaviours of the liquid sheets formed by the impingement of two water jets (figure 9a) or the impingement of water and MCH jets (figure 9b)
Figure 7. Typical sequences of sheet breakups observed in the 0.10 MPa air atmosphere. \( \theta = 120^\circ \). (a) Breakup of a water sheet formed by the impingement of two water jets; \( \dot{V}_w = 70 \text{cm}^3\text{min}^{-1} \) (\( Re_{j,w} = 3339 \)). (b) Breakup of a dual-layer sheet formed by the impingement of the water and MCH jets; \( \dot{V}_w = 60 \text{cm}^3\text{min}^{-1} \) (\( Re_{j,w} = 2862 \)). Note that these sequences were taken using the high-pressure setup (figure 2b) equipped with paired nozzles made of stainless-steel tubes instead of Pyrex capillaries. The critical water flow rate \( \dot{V}_{w,cr} \) for the transition from the steady-sheet regime to the intermittent sheet-breakup regime was reduced to approximately 60 cm\(^3\) min\(^{-1}\) for the water–water system and approximately 50 cm\(^3\) min\(^{-1}\) for the water–MCH system. That is, the water flow rate maintained in each sequence was within the intermittent sheet-breakup regime for the relevant system.
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Figure 8. Characteristics of intermittent sheet breakup for the impingement of two water jets injected into 0.10 MPa air. \( 2\theta = 120^\circ \). The intervals each spanning \( \tau_b \) and the frequency \( f_b \) of sheet breakups (a) and the volume of water supplied through each nozzle during each interval \( \dot{V}_w \tau_b \) (b) are plotted versus the water flow rate through the nozzle \( \dot{V}_w \) or the water-jet velocity \( U_{j,w} \). Each data point for \( \tau_b \) or \( \dot{V}_w \tau_b \) (filled circle) represents the average over 20 intervals of successive breakups. The error bar laid on the point indicates the standard deviation of these 20 individual data from the average. Each data point for \( f_b \) (open triangle) represents the reciprocal of the corresponding average of the \( \tau_b \) data.

Vary with an increase in the ambient pressure, \( p \). Analogous to figure 5, the length \( L \) and width \( W \) of these sheets are plotted versus \( \dot{V}_w \) and \( Re_{j,w} \) in figure 10. Note that in the case of impingement of two water jets at atmospheric pressure \( (p = 0.101 \text{ MPa}) \), the formation of a sheet with a closed rim and its breakup periodically repeated at a flow rate of \( \dot{V}_w = 60 \text{ cm}^3 \text{ min}^{-1} \), which is over 10 cm\(^3\) min\(^{-1}\) less than the critical flow rate observed with the other setup (figure 2a) in which Pyrex capillaries were used as nozzles (cf. figure 5). It is likely that a slightly larger inner-wall roughness of the stainless-steel nozzles used in the setup for higher-pressure use (figure 2b) promoted the transition from the steady-sheet regime to the intermittent sheet-breakup regime. Except for the above difference in the regime-to-regime transition condition, we recognized no

Figure 9. Observations of jet impingement in nitrogen-gas atmosphere at elevated pressures. \(2\theta = 120^\circ\). (a) Impingement of the two water jets and (b) impingement of the water and MCH jets. Scale bars, (a) 5 mm; (b) 3 mm.

substantial difference in the sheet-formation/breakup behaviour in the normal-pressure air between the two experimental setups. Visually, the most remarkable effect of the increasing pressure was the collapse of the lower part of each sheet.
within the steady-sheet regime, which provided the sheet with an open-rim configuration characterized by a ragged bottom from where tiny droplets were generated (see the pictures for $p = 2.1$ and $3.1$ MPa and $\dot{V}_w = 40$ and $50$ cm$^3$ min$^{-1}$).
Figure 10. Evolution of the sheet size with the increasing water flow rate $\dot{V}_w$ or the water-jet Reynolds number $Re_{j,w}$. Except for those obtained in the normal-pressure (0.10 MPa) air atmosphere, all data were obtained in a pressure-controlled nitrogen-gas atmosphere. These data are plotted here in a graphical arrangement analogous to that in figure 5. The sheet formed by the impingement of the two water jets at $\dot{V}_w = 60 \text{ cm}^3 \text{ min}^{-1}$ and $p = 0.10 \text{ MPa}$ took alternately, although not regularly, a larger smooth-faced form with a closed rim and a smaller ruffled form exhibiting intermittent breakups. Thus, the length and width measured with each of these two forms are indicated here. Filled circles, $p = 0.1 \text{ MPa}$; open circles, $p = 1.1 \text{ MPa}$; filled triangles, $p = 2.1 \text{ MPa}$; open triangles, $p = 3.1 \text{ MPa}$.

in figure 9a and the one for $p = 3.1 \text{ MPa}$ and $\dot{V}_w = 40 \text{ cm}^3 \text{ min}^{-1}$ in figure 9b). This finding is discussed later in more detail. Also recognized in both figures 9 and 10 are a decreasing sheet size and an increasing intensity of atomization with the increasing pressure in the intermittent sheet-breakup regime.

The system-pressure dependency of the sheet breakup and atomization as demonstrated in figures 9 and 10 must have resulted from an increased instability on each sheet with an increasing pressure, which possibly originated from the instability developed on jets in advance of their mutual collision. Figure 11 shows side-view snapshots of water jets at a flow rate around the border of the two regimes, $\dot{V}_w = 50 \text{ cm}^3 \text{ min}^{-1}$, and MCH jets at the corresponding flow rate, $\dot{V}_{\text{MCH}} = 57 \text{ cm}^3 \text{ min}^{-1}$, observed at normal and elevated pressures. These snapshots show that the inception and axial growth of a disturbance on a water jet are promoted by an increase in pressure, and that an MCH jet, which is obviously in a turbulent-flow condition at the nozzle outlet, is also increasingly
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Figure 11. Side-view snapshots of liquid jets injected into normal-pressure air (0.10 MPa) or pressurized nitrogen: (a) water jet, \( \dot{V}_w = 50 \text{ cm}^3 \text{ min}^{-1} \) and (b) MCH jet, \( \dot{V}_{\text{MCH}} = 57 \text{ cm}^3 \text{ min}^{-1} \). (a, b) Scale bars, 5 mm.

disturbed along its axis and with an increase in pressure. Such an undulation of each of the paired jets inevitably prevents their axes from continuously crossing each other on the vertical plane on which a sheet lies. That is, if either or both of them are undulating, the paired jets are unavoidably brought into an offset collision, in which the lateral gap between their axes on the above plane fluctuates with time, thereby generating nearly concentric waves radially propagating on the sheet and, if \( \dot{V}_w > \dot{V}_{w,\text{cr}} \), inducing the intermittent breakup of the sheet. Figures 9 and 11 show that as expected from the nature of the Kelvin–Helmholtz instability, the disturbances on the jets and the sheet tend to be intensified with an increase in the system pressure, i.e. with an increase in the density of the surrounding gas phase. This tendency is considered to be the cause of the decrease in \( \dot{V}_{w,\text{cr}} \) and also the reduction in the sheet size in the intermittent sheet-breakup regime with an increase in the pressure.

The most conspicuous feature of the sheets formed at elevated pressures was the open-rim configuration that appeared in the higher flow-rate part of the steady-sheet regime. This sheet-configuration mode is most clearly recognized in the snapshot for \( \dot{V}_w = 50 \text{ cm}^3 \text{ min}^{-1} \) and \( p = 2.1 \) or 3.1 MPa given in figure 9(a). This mode is also recognized, although relatively less clearly, in the snapshot for \( \dot{V}_w = 40 \text{ cm}^3 \text{ min}^{-1} \) and \( p = 3.1 \) MPa in figure 9(b). A more comprehensive set of snapshots of the open-rim sheets formed by the impingement of two water jets is shown in figure 12. In general, the open-rim mode is characterized by the collapse of the lower part of each sheet in the form of droplet ejection from many locations distributed over the entire width of the lower periphery of the sheet. Obviously, a much larger number of much smaller droplets are generated at the lower periphery, compared with those released from the rim fringing the upper part of the sheet.

Our experiments showed that as far as the liquid-jet impingement is concerned, the formation of such open-rim sheets as those discussed earlier is limited only to a high ambient pressure range (approx. 2 MPa or higher), in which the density of the surrounding gas exceeds 22 kg m\(^{-3}\). To the best of our knowledge, the formation of such open-rim sheets has not been observed in previous liquid-jet
Figure 12. Liquid sheets with unclosed rims. The snapshots aligned here were taken in the experiments using two water jets issuing into nitrogen gas from nozzles fixed at $2\theta = 120^\circ$: (a) $\dot{V}_w = 40 \text{ cm}^3 \text{ min}^{-1}$ and (b) $\dot{V}_w = 50 \text{ cm}^3 \text{ min}^{-1}$. The stable, bilaterally symmetric shape of the laminar liquid sheets each contoured by an elliptic or cardioid rim was lost at elevated pressures (approx. 2.1 MPa or above) due to the collapse of the lower portion of each sheet, which prevented its rim from being closed and forming an acute tip at the bottom of the sheet. (a,b) Scale bars, 5 mm.

impingement studies. It should be noted, however, that if we do not confine this issue to the case of liquid-jet impingement, the formation of open-rim sheets is not new; in fact, such sheets are readily formed by using, for example, fan-spray nozzles or slot-type orifices even under atmospheric pressure (see Dombrowski & Fraser 1954; Crapper et al. 1973; Mansour & Chigier 1990). The simultaneous formation of larger droplets from the edge of the rim and finer droplets at the lower periphery of such an open-rim sheet is already well recognized (see fig. 18 and its caption in Villermaux & Clanet (2002) and fig. 1 and relevant text description in Bremond et al. (2007)).

Sheets with open rims are generally accompanied by longitudinal wrinkles (or waves), which are azimuthally distributed over the lower periphery of each sheet. Our high-speed videographic observations have revealed that the formation and ejection of droplets from the lower periphery of each open-rim sheet are closely related to such longitudinal wrinkles. We describe below how the longitudinal wrinkles emerge on a sheet and how they interact with the droplet formation/ejection at the lower periphery of the sheet. The longitudinal wrinkles generally emerge only in the lower peripheral region on each sheet just in front of one, or at most a few, of the transverse wrinkles travelling towards the lower periphery. The typical geometries and orientations of such transverse and longitudinal wrinkles are shown in figure 13a. Figure 13b exemplifies a sequence
in which we can follow the translation and evolution in shape of a particular longitudinal wrinkle (marked by a blue circle). This wrinkle moved to the lower edge of the sheet and, while traversing along the edge towards the centre line of the sheet, broke through the edge, taking the form of a thread like a ‘string of beads’, and released droplets (marked by the red circles) into the surrounding gas. These observations of the transformation of each longitudinal wrinkle to each thread and a droplet train jutting into the gas phase indicate that the wrinkles are not the crests of a sinuous wave, but the ribs grown from a varicose wave (Lin 2003).

(c) Atomization behaviour

Droplets falling in normal-pressure air (0.101 MPa) were photographed at a location approximately 150 mm down from the point of jet collision at a magnification suitable for measuring their size with the aid of a conventional particle-image analysis procedure. The setup for normal-pressure use (figure 2a) was exclusively used. No attempt was made to measure the droplet size at elevated pressures because of the technical difficulty in applying such photography at a larger magnification to the other setup (figure 2b). The vertical location of approximately 150 mm down from the point of jet collision was selected, considering the time required for sufficient damping of the shape oscillation induced on droplets at their release from the sheet. The primary objective of this class of experiments was to reveal how the impingement of two mutually immiscible liquids, water and MCH, work on their atomization and mutual mixing; i.e. more specifically, to examine whether the two liquids merged in each of the formed droplets (as expected in §3a) and to evaluate how small these droplets are, compared with those formed by the impingement of two equal water jets. Figure 14 shows typical droplet images obtained in the above experiments. Each droplet shown here is composed of a water core and an MCH shell that encapsulates, at least in part, the water core. This observation is consistent with the free-energy-based prediction that the mutual contact of a water droplet and a hydrocarbon droplet in the gas phase should result in their coalescence into a composite droplet in which a hydrocarbon phase covers almost the whole surface of a water phase, such that the total surface free energy in a droplet-holding space is minimized (Mori et al. 1981). We also note that the water core in each droplet generally contains several tiny air bubbles.

Figure 15 shows the variation in the Sauter mean diameter of droplets depending on the jet-collision angle $2\theta$ and the water-jet Reynolds number $Re_{j,w}$ for both the impingement of two water jets and that of the water and MCH jets. Note that the data shown here are based on the size measurements with droplets captured in a rectangular area, which horizontally extended 22 mm about the central axis of the vertical plane on which the liquid sheets expanded and vertically extended 15 mm about the level of approximately 150 mm down from the location of the jet collision. Because the droplet size may have some spatial distribution in the lateral direction (Anderson et al. 1995), each data point plotted in figure 15 may not accurately represent the mean diameter of all droplets passing the level of approximately 150 mm down from the location of the jet collision. Nevertheless, we can still compare, in
Figure 13. Emergence of transverse and longitudinal wrinkles on a water sheet with an unclosed rim. (a) A snapshot picture of the entire figure (left) and an enlarged picture of the near-bottom portion of the sheet (right). Scale bar, 5 mm. (b) A sequence of the translation and evolution in shape of longitudinal wrinkles captured by a high-speed video camera. All pictures shown here were obtained in an experiment using two water jets issuing into 4.0 MPa nitrogen gas from nozzles fixed at $2\theta = 120^\circ$. $\dot{V}_w = 40 \text{ cm}^3 \text{ min}^{-1}$.

Figure 14. Falling droplets formed by the impingement of water and MCH jets in 0.10 MPa air atmosphere. $\dot{V}_w = 30 \text{ cm}^3 \text{ min}^{-1}$ ($Re_{j,w} = 1431$). Note that each droplet shown here is composed of a water core and an MCH shell that encapsulates, at least in part, the water core. The water core contains several tiny air bubbles. Scale bar, 2 mm.
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Figure 15. Sauter mean diameters of droplets formed by the jet impingement in 0.10 MPa air atmosphere: (a) impingement of the two water jets and (b) impingement of the water and MCH jets. Each point and accompanied error bar represent the mean and the standard deviation, respectively, of 100 sample droplet images, which have circularity ratios higher than 0.95. Filled circles, $2\theta = 60^\circ$; open circles, $2\theta = 90^\circ$; filled triangles, $2\theta = 120^\circ$.

In this figure, the atomization characteristics of the water–water impingement and that of the water–MCH impingement. The most remarkable difference in the atomization characteristics of the water–MCH impingement from the water–water impingement is the substantial reduction in the droplet size in the intermittent sheet-breakup regime, which is realized when the jet-collision angle is rather large ($2\theta = 90^\circ$ or $120^\circ$). This characteristic may effectively be used in some applications such as the structure-H hydrate formation (Murakami et al. 2009).

4. Conclusions

An observational study has been carried out on the impingement of two cylindrical liquid jets of either the same liquid, water, or two mutually immiscible liquids, water and MCH, in either air under normal pressure (0.101 MPa) or
nitrogen gas under pressures elevated up to 4.0 MPa. The water-jet Reynolds number ($Re_{j,w}$) and Weber number ($We_{j,w}$) ranged from 1400 to 4800 and from 45 to 500, respectively. The major findings obtained in this study are as follows.

— In common with the impingement of two equal water jets, the impingement of the water and MCH jets generates an expanding sheet, which exhibits an apparently steady, elliptic or cardioid shape in the lower $Re_{j,w}$ ($We_{j,w}$) range, but a wrinkled, unsteady shape intermittently deformed by azimuthal breakups in the higher $Re_{j,w}$ ($We_{j,w}$) range. The transition from the steady-sheet regime to the intermittent sheet-breakup regime in this case occurs at a lower value of $Re_{j,w}$ ($or$ $We_{j,w}$) compared with that for the impingement of two water jets.

— Each sheet formed by the impingement of water and MCH jets is, in general, a dual film composed of a water layer and an MCH layer.

— An increase in the system pressure reduces the sheet size, promotes the transition from the steady-sheet regime to the intermittent sheet-breakup regime, and intensifies the liquid atomization.

— At elevated pressures (approx. 2.1 MPa or above), the lower part of each sheet formed in the higher $Re_{j,w}$ part of the steady-sheet regime collapses, exhibiting an unstable bottom periphery accompanied by laterally distributed wrinkles each disintegrating into tiny droplets, which are ejected from the periphery.

— The impingement of the water and MCH jets forms compound droplets, each composed of a water core and an MCH shell that encapsulates, at least in part, the water core. Such compound droplets formed in the intermittent sheet-breakup regime are substantially smaller than the water droplets formed by the impingement of two water jets at the same water flow rate when the angle of the jet collision is fixed at 90° or 120°.

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