Class Notes
Introduction to fluid mechanics

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Contents

1 The Equation of Motion

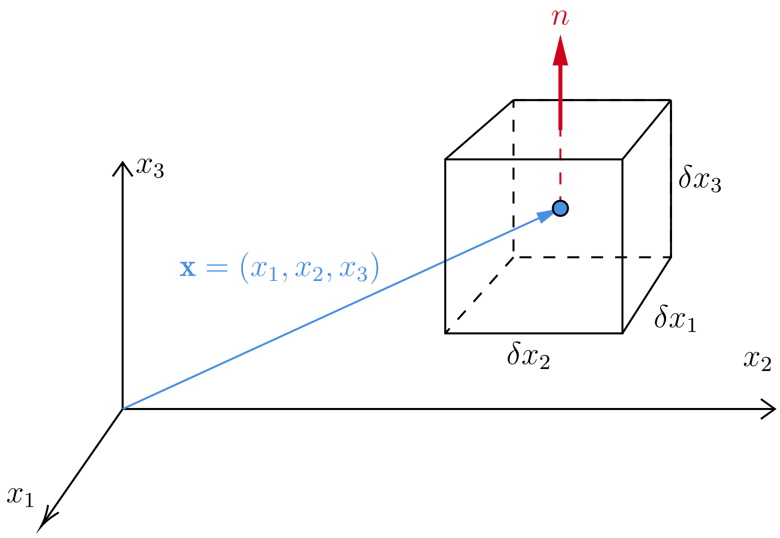
1.1 Introduction

1.1.1 Euler's equation:

Consider a fluid in a domain D in $\mathbb{R}^n$ ($n = 2$, $n = 3$).

Let $x \in D$, and $\rho(\mathbf{x}, t)$, $\mathbf{u}(\mathbf{x}, t)$, $p(\mathbf{x}, t)$ be the fluid density, velocity vector field and the pressure at the point x and time t.Consider an infinitesimal element of the fluid of volumn ∂V located at point x at time t with mass $\delta m = \rho(\mathbf{x}, t)$, which is moving $\mathbf{u}(\mathbf{x}, t)$ and momentum $\delta m \cdot \mathbf{u}(\mathbf{x}, t)$

The normal force directed into the indeinetesmal volumn across a face of area δa is $\mathbf{n} \cdot p(\mathbf{x}, t) \cdot \delta a$



Note that the pressure is the magnitade of the torce per unit area or normal stress, imposed on the fluid from neighboring fluid elements.

1.1.2 Convective derivative

convective derivative 對流導數 / material derivative 物質導數 / advective derivative 隨流導數 / convective derivative 對流導數 / derivative following the motion 隨體導數 / hydrodynamic derivative 水動力導數 / Lagrange derivative 拉格朗日導數 / substantial derivative 隨質導數 Couvder a fluid particle moving in flaid, whose position $\mathbf{x}$ at time t is $\mathbf{x}(t)$. Then

$$\frac{d\mathbf{x}(t)}{dt} = \dot{\mathbf{x}} = \mathbf{u}(\mathbf{x}(t), t) \tag{1}$$

Hence, if $f(\mathbf{x}, t)$ is a function on $D \times (0, T)$, then $f(\mathbf{x}(t), t)$ is the value if f at the moving fluid particle at $\mathbf{x}(t)$ at time t. We define the convective derivative of f:

$$\begin{aligned} \frac{Df(\mathbf{x}, t)}{Dt} &= \frac{\partial f(\mathbf{x}, t)}{\partial t} + \dot{\mathbf{x}} \cdot \nabla f(\mathbf{x}, t) \\ &= f_t + \mathbf{u} \cdot \nabla f \end{aligned} \tag{2}$$

where $\nabla f = f(f_x, f_y, f_z)$ and $\mathbf{u} = (u_1, u_2, u_3)$.

Hence, if $f(\mathbf{x},t)$ is a function on $D\times(0,T)$, then $f(\mathbf{x}(t),t)$ is the vlaue of f at the moving fluid particle at $\mathbf{x}(t)$ at time t.

We define the convective derivative of f as:

$$\begin{aligned}\frac{Df(x,t)}{Dt} &= \frac{\partial f}{\partial t} + \dot{\mathbf{x}}(t)\cdot\nabla f \\ &= f_t + \mathbf{u}\cdot\nabla f\end{aligned}, \tag{3}$$

where $\nabla f = (f_x, f_y, f_z)$ and $\mathbf{u} = (u_1, u_2, u_3)$.

1.1.2.1 Def.

For any vector filed $\mathbf{F} = (F_1, F_2, \ldots, F_n)$ on D, we let

$$\int_D \mathbf{F}dV = \left(\int_D F_1 dV, \int_D F_2 dV, \ldots, \int_D F_n dV\right). \tag{4}$$

1.1.2.2 Def.

We will assume that D is a smooth domain, i.e. for any $x_0\in\partial D$, $\mathbb{R}^n = (x', x_n), n = 2,3$ $\exists\delta_0 > 0$ and a smooth function $\varphi:\mathbb{R}^{n-1}\to\mathbb{R}$, s.t.

$$\partial D\cap B(x_0,\delta_0) = \left\{(x',\varphi(x')) : \|x'\| < \delta_0, x'\in\mathbb{R}^{n-1}\right\}\cap B(x_0,\delta_0) \tag{5}$$

and

$$D\cap B(x_0,\delta_0) = \left\{(x',x_n) : x_n > \varphi(x'), x'\in\mathbb{R}^{n-1}, \|x'\| < \delta_0\right\}\cap B(x_0,\delta_0) \tag{6}$$

1.1.2.3 Claim

Conside the volume δV of an element of mass δm, which moves in the fluid by the fluid motion

$$\frac{d(\delta V)}{dt} = (\nabla\cdot\mathbf{u})(\mathbf{x},t)\cdot\delta V \quad \text{as} \quad \delta x_1, \delta x_2, \delta x_3 \to 0, \tag{7}$$

where $\nabla\cdot\mathbf{u} = \operatorname{div}\mathbf{u} = \sum_{i=1}^{3}\frac{\partial u_i}{\partial x_i}$, $\mathbf{u} = (u_1, u_2, u_3)$.

1.1.2.4 proof

$$\begin{aligned}\frac{d(\delta V)}{dt} &= \frac{d}{dt}(\delta x_1, \delta x_2, \delta x_3) \\ &= \frac{d(\delta x_1)}{dt}\delta x_2\delta x_3 + \frac{d(\delta x_2)}{dt}\delta x_1\delta x_3 + \frac{d(\delta x_3)}{dt}\delta x_1\delta x_2\end{aligned} \tag{8}$$

For the first term

$$\begin{aligned}\frac{d(\delta x_1)}{dt} &\approx u_1\left(x_1 + \frac{\delta x_1}{2}, x_2, x_3\right) - u_1\left(x_1 - \frac{\delta x_1}{2}, x_2, x_3\right) \\ &= \frac{\partial u_1}{\partial x_1}(\xi_1, x_2, x_3)\delta x_1, \quad \text{fot some } \xi_1\in\left(x_1 - \frac{\delta x_1}{2}, x_1 + \frac{\delta x_1}{2}\right)\end{aligned} \tag{9}$$

then

$$\frac{d(\delta x_1)}{dt}\delta x_2\delta x_3 \to \frac{\partial u_1}{\partial x_1}(x_1, x_2, x_3)\delta x_1\delta x_2\delta x_3, \quad \text{as } \delta x_1, \delta x_2, \delta x_3 \to 0 \tag{10}$$

Similarly

$$\frac{d(\delta x_2)}{dt}\delta x_2\delta x_3 \to \frac{\partial u_2}{\partial x_1}(x_1,x_2,x_3)\delta x_1\delta x_2\delta x_3, \quad \text{as } \delta x_1,\delta x_2,\delta x_3 \to 0 \tag{11}$$

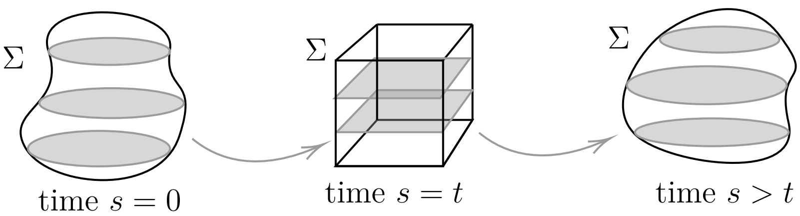
and

$$\frac{d(\delta x_3)}{dt}\delta x_2\delta x_3 \to \frac{\partial u_3}{\partial x_1}(x_1,x_2,x_3)\delta x_1\delta x_2\delta x_3, \quad \text{as } \delta x_1,\delta x_2,\delta x_3 \to 0 \tag{12}$$

so that

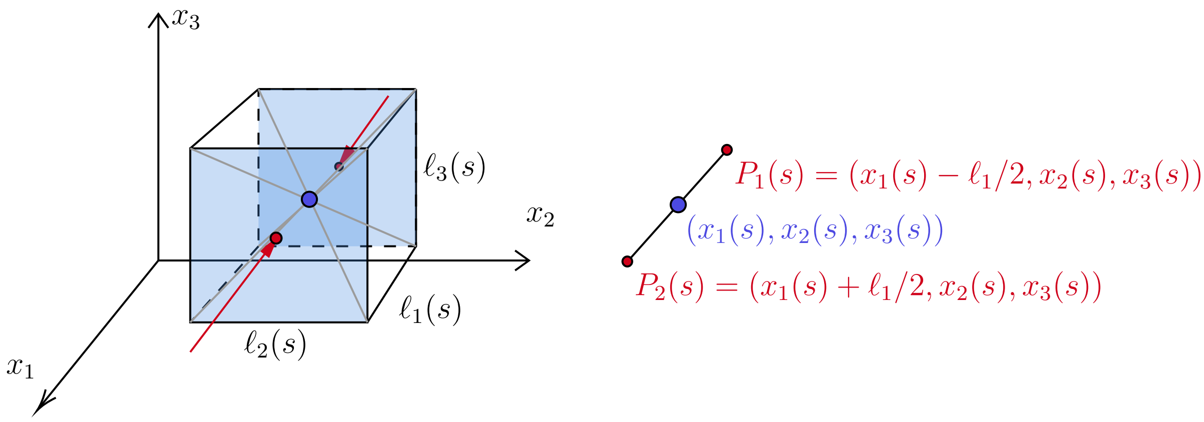
$$\frac{d(\delta V)}{dt} = \left(\frac{\partial u_1}{\partial x_1}+\frac{\partial u_2}{\partial x_2}+\frac{\partial u_3}{\partial x_3}\right)\delta x_1\delta x_2\delta x_3 = (\nabla\cdot\mathbf{u})\delta V \tag{13}$$

1.1.2.5 Note



tagged porton of fluid particle

Consider a a tagged (marked) portion Σ of fluid with center of mass at $(x_1(s),x_2(s),x_3(s))$ at time s. Let $m(x)$ and $V(s)$ be the mass and volumn of this portion Σ of fluid at time s.The portion of fluid particle moves aling with fluid. see as (2/21 fig1)



For a time $t>0$, suppose at time t, the tagged portion Σ of fluid particles is a cube centered at (x_1,x_2,x_3) with side lengh ℓ_1,ℓ_2,ℓ_3, see as (2/21 fig2 - textbook p.4),where

$$\begin{aligned} P_1(s) &= \left(x_1(s) - \frac{\ell_1(s)}{2}, x_2(s), x_3(s)\right) \\ P_2(s) &= \left(x_1(s) + \frac{\ell_1(s)}{2}, x_2(s), x_3(s)\right) \end{aligned} \tag{14}$$

We assume that Σ remain a cube for $s\approx t$ with side length, $\ell_1(s),\ell_2(s),\ell_3(s)$, then $V(s)=\ell_1(s)\cdot\ell_2(s)\cdot\ell_3(s)$

$$\left.\frac{dV(s)}{ds}\right|_{s=t} = \left.\frac{d\ell_1(s)}{ds}\right|_{s=t}\ell_2(s)\ell_3(s) + \left.\frac{d\ell_2(s)}{ds}\right|_{s=t}\ell_1(s)\ell_3(s) + \left.\frac{d\ell_3(s)}{ds}\right|_{s=t}\ell_1(s)\ell_2(s) \tag{15}$$

where

$$
\begin{aligned}
\frac{d\ell_1(s)}{ds} &= u_1(P_2(t),t) - u_1(P_1(t),t) \\
&= u_1\left(x_1(s) + \frac{\ell_1(s)}{2}, x_2(s), x_3(s), t\right) - u_1\left(x_1(s) - \frac{\ell_1(s)}{2}, x_2(s), x_3(s), t\right) \\
&\approx \frac{\partial u_1}{\partial x_1}(x_1, x_2, x_3, t) \cdot \ell_1
\end{aligned}
\tag{16}
$$

Similarly

$$
\left.\frac{d\ell_i}{ds}\right|_{s=t} = \frac{\partial u_i}{\partial x_i}(x_1, x_2, x_3) \cdot \ell_i, \quad \forall i = 1, 2, 3. \tag{17}
$$

Now we write $\left.\frac{d}{ds}\right|_{s=t} = \frac{d}{dt}$, combinded with equation

1.1.3 Continuity equation

Let $\rho(\mathbf{x}, t)$ be the density of fluid at time s.Since $M(s) = \text{const.}$, $\forall s > 0$ and $\frac{dM(s)}{ds} = 0$, $\forall s > 0$.Therefore, since it is similar to the cube, the density is

$$
\rho(\mathbf{x}, s) \approx \frac{M(s)}{V(s)} \tag{18}
$$

and the derevative is

$$
\begin{aligned}
\left.\frac{d}{ds}\rho(\mathbf{x}, s)\right|_{s=t} &\approx \left.\frac{d}{ds}\frac{M(s)}{V(s)}\right|_{s=t} \\
&= \left.\frac{M'(s)V(s) - M(s)V'(s)}{V^2(s)}\right|_{s=t} \\
&= \left.\frac{0 - M(s)\frac{d}{ds}V(s)}{V^2(s)}\right|_{s=t} \\
&= \left.-\frac{M(s)(\operatorname{div}\mathbf{u})V(s)}{V^2(s)}\right|_{s=t} \\
&= \left.-\frac{M(s)}{V(s)}(\operatorname{div}\mathbf{u}(s))\right|_{s=t} \\
&= \left.-\rho(\mathbf{x}(s), s)(\operatorname{div}\mathbf{u}(s))\right|_{s=t}
\end{aligned}
\tag{19}
$$

we get

$$
-\frac{d}{dt}\rho(\mathbf{x}(t), t) = \rho \cdot (\nabla \cdot \mathbf{u}(t)) \tag{20}
$$

On the other hand, by chain rule

$$
\frac{d}{dt}\rho(\mathbf{x}(t), t) = \rho_t + (\nabla\rho) \cdot \mathbf{u}(t) \tag{21}
$$

combining together we have

$$\begin{aligned}
&\Rightarrow \rho_t + (\nabla\rho)\cdot\mathbf{u} = \rho\cdot(\nabla\cdot\mathbf{u})\\
&\Rightarrow \rho_t + (\nabla\rho)\cdot\mathbf{u} - \rho\cdot(\nabla\cdot\mathbf{u}) = 0\\
&\Rightarrow \rho_t + \nabla\cdot(\rho\mathbf{u}) = 0
\end{aligned}\tag{22}$$

and the equation $\rho_t + \nabla\cdot(\rho\mathbf{u}) = 0$ is called the *contunuity equation.*

1.1.4 Heuristic proof of the Euler equation

In the ansense of an externally applied forces, the net force $\mathbf{F}$, acting on δV, is due to the pressure field.

Write $\mathbf{F} = (F_1, F_2, F_3)$, we get

$$\begin{aligned}
\mathbf{F}(x_1,x_2,x_3,t) &\approx \left(P\left(x_1 - \frac{\delta x_1}{2}, x_2, x_3, t\right) - P\left(x_1 + \frac{\delta x_1}{2}, x_2, x_3, t\right)\right)\delta x_2\delta x_3\\
&= -\frac{\partial P}{\partial x_1}(\zeta_1, x_2, x_3, t)\delta x_1\delta x_2\delta x_3, \quad \delta x_1, \delta x_2, \delta x_3 \to 0\\
&= \frac{\partial P}{\partial x_1}(\zeta_1, x_2, x_3, t)\delta V
\end{aligned}\tag{23}$$

for some $\zeta_1 \in \left(x_1 - \frac{\delta x_1}{2}, x_1 + \frac{\delta x_1}{2}\right)$.

By Newton's second law, the equation of motion for the elemnet of fund mass δm, at point $\mathbf{x}(t)$ is

$$\frac{d}{dt}\left(\delta m\cdot\mathbf{u}(\mathbf{x},t)\right) = \mathbf{F} = -(\nabla P)\delta V\tag{24}$$

also

$$\frac{d}{dt}\left(\delta m\cdot\mathbf{u}(\mathbf{x},t)\right) = \delta m\frac{d}{dt}\mathbf{u}(\mathbf{x},t) = \delta m\left(\mathbf{u}_t + (\nabla\cdot\mathbf{u})\right)\mathbf{u}\tag{25}$$

then

$$\begin{aligned}
\delta m\left(\mathbf{u}_t + (\nabla\cdot\mathbf{u})\right)\mathbf{u} &= -(\nabla P)\delta V\\
\mathbf{u}_t + (\nabla\cdot\mathbf{u})\,\mathbf{u} &= -(\nabla P)\frac{\delta V}{\delta m} = -(\nabla P)\frac{1}{\delta m/\delta V}
\end{aligned}\tag{26}$$

we get a equation

$$\mathbf{u}_t + (\nabla\cdot\mathbf{u})\,\mathbf{u} = -\frac{\nabla P}{\rho}\tag{27}$$

called *Euler's equation.*

Notice that

$$\begin{aligned}
(\nabla\cdot\mathbf{u})\;\mathbf{u} &= \left(\sum_{i=0}^{3} u_i\frac{\partial}{\partial x_i}\right)\mathbf{u}\\
&= \left(u_1\frac{\partial}{\partial x_1} + u_2\frac{\partial}{\partial x_2} + u_3\frac{\partial}{\partial x_3}\right)\begin{pmatrix}u_1\\u_2\\u_3\end{pmatrix}\\
&= \begin{pmatrix}\left(u_1\frac{\partial}{\partial x_1} + u_2\frac{\partial}{\partial x_2} + u_3\frac{\partial}{\partial x_3}\right)u_1\\ \left(u_1\frac{\partial}{\partial x_1} + u_2\frac{\partial}{\partial x_2} + u_3\frac{\partial}{\partial x_3}\right)u_2\\ \left(u_1\frac{\partial}{\partial x_1} + u_2\frac{\partial}{\partial x_2} + u_3\frac{\partial}{\partial x_3}\right)u_3\end{pmatrix}
\end{aligned}\tag{28}$$

1.1.5 Lemma

Let D be a bounded domain and $F : \bar{D} \times [0, a_0] \to \mathbb{R}$ be a smooth function (or C^∞), then

$$\frac{d}{dt}\int_D F(x,t)dx = \int_D \frac{dF(x,t)}{dt}dx \tag{29}$$

1.1.5.1 proof

we have

$$\begin{aligned}
\frac{d}{dt}\int_D F(x,t)dx &= \lim_{\Delta t\to 0}\left[\frac{1}{\Delta t}\int_D F(x,t+\Delta t)dx - \frac{d}{dt}\int_D F(x,t)dx\right] \\
&= \lim_{\Delta t\to 0}\frac{d}{dt}\int_D \frac{F(x,t+\Delta t)-F(x,t)}{\Delta t}dx \\
&= \text{By M.V.T.} \\
&= \lim_{\Delta t\to 0}\int_D \frac{\frac{\partial}{\partial t}F(x,\xi)\Delta t}{\Delta t}dx, \quad \text{for some } \xi, \text{ where} t < \xi < t+\Delta \\
&= \lim_{\Delta t\to 0}\int_D \frac{\partial}{\partial t}F(x,\xi)dx
\end{aligned} \tag{30}$$

Denote, $\frac{\partial}{\partial t}F(x,t) = F_t(x,t)$ and $\frac{\partial^2}{\partial t^2}F(x,t) = F_{tt}(x,t)$, so

$$\begin{aligned}
&\left|\frac{1}{\Delta t}\int_D [F(x,t+\Delta t)-F(x,t)] - \int_D \frac{\partial}{\partial t}F(x,t)dx\right| \\
&= \left|\int_D F_t(x,\xi)dx - \int_D F_t(x,\xi)dx\right| \\
&= \text{By MVT} \\
&= \left|\int_D [F_t(x,\xi)-F_t(x,t)]\right|dx \\
&= \text{By MVT} \\
&= \left|\int_D F_{tt}(x,z)(t-\xi)dz\right|, \quad z \text{ between } t \text{ and } \xi \\
&\le M|t-\xi||D| \to 0, \quad \text{where } |D| \text{ is vlolumn of } D
\end{aligned} \tag{31}$$

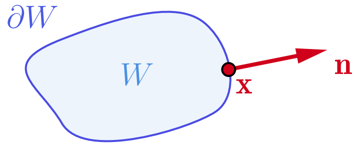
where $M = \sup\limits_{(x,t)\in D\times(0,a)} F_{tt}(x,t)$.

1.1.6 The Continuity Equation

Recall that D is a region in $\mathbb{R}^2$ or $\mathbb{R}^3$ filled with fluid and $x = x(x_1, x_2, x_3) \in D$ is a particle of fluid moving through x at time t with velocity $\mathbf{u}(x,t)$. If W is a ant subregion of D, then the mass of fluid in W at time t is

$$m(W,t) = \int_W \rho(x,t)dV, \tag{32}$$

where $\rho(x,t)$ is the density of fluid at (x,t). Then $\frac{d}{dt}m(W,t) = \int_W \rho_t(x,t)dV$.



Let ∂W be the boundary of W. Suppose ∂W is smooth, let $\mathbf{n}(x)$ be the normal vector to ∂W at $x \in \partial W$, Let dA denote the

Then the volumn of fluid flow rate across ∂W per unit time, Since $\mathbf{u} \cdot \mathbf{n}\,\Delta A \Rightarrow$ the mass of fluid flow per unit time is $\rho\mathbf{u} \cdot \mathbf{n}\,\Delta A$

Since, by the conservation of mass, the rate of increase of mass in W is equal to the rate that mass is incoming ∂W

$$\int_W \rho_t dV = \frac{d}{dt}\int_W \rho dV = -\int_{\partial W} \rho\,(\mathbf{n} \cdot \mathbf{u}) dV = \text{by divergence theorem} = -\int_W \operatorname{div}(\rho\mathbf{u}) dV \tag{33}$$

By divergence theorem, we have

$$\int_W \left(\rho_t + \operatorname{div}(\rho\mathbf{u})\right) dV = 0, \quad \forall W \subset D \tag{34}$$

We now choose $W = B(x,r)$, and let $H(y,t) = \rho_t + \operatorname{div}(\rho\mathbf{u}) = H$, by above equation, we have

$$\int_{B(x,r)} H(y,t) dV_x = 0, \quad \forall x \in D, B(x,r) \subset D \tag{35}$$

Notice $H(y,t) = \dfrac{1}{|B(x,r)|}\displaystyle\int_{B(x,r)} H(y,t) dV = H(y,t)\dfrac{\int_{B(x,r)} dV}{|B(x,r)|}$, where $|B(x,r)|$ is the volumn of $B(x,r)$. Now

$$\begin{aligned}
\left|\frac{1}{B(x,r)}\int_{B(x,r)} H(x,t) dV - H(x,t)\right| &= \frac{1}{|B(x,r)|}\left|\int_{B(x,r)} [H(y,t) - H(x,t)] dV\right| \\
&\leq \frac{1}{|B(x,r)|}\int_{B(x,r)} |H(y,t) - H(x,t)| dV \\
&\leq \frac{1}{|B(x,r)|}\max_{y \in B(x,r)} |H(y,t) - H(x,t)| \cdot |B(x,r)| \\
&\to 0, \quad \text{as } r \to 0
\end{aligned} \tag{36}$$

so that

$$\lim_{r\to 0}\left|\frac{1}{B(x,r)}\int_{B(x,r)} H(x,t) dV - H(x,t)\right| = 0 \tag{37}$$

By equation (35) and (37), we have

$$H(x,t) = 0 \quad \Rightarrow \quad \rho_t + \operatorname{div}(\rho\mathbf{u}) = 0 \tag{38}$$

which is called the continuity equation in $D \times (0,T)$.

1.2 Proof of Euler's Equation

1.2.1 Balance of Momentum 1 (BM1)

The force per unit area on a point $x \in \partial W$ is $-p \cdot \mathbf{n}$, since the total force on W due force the pressure on ∂W is

$$\begin{aligned}
\mathbf{f} &= -\int_{\partial W} p \cdot \mathbf{n} dA \\
&= \left(-\int_{\partial W} pn_1 dA, -\int_{\partial W} pn_2 dA, -\int_{\partial W} pn_3 dA \right) \\
&= \left(-\int_{\partial W} (p,0,0) \cdot \mathbf{n} dA, -\int_{\partial W} (0,p,0) \cdot \mathbf{n} dA, -\int_{\partial W} (0,0,p) \cdot \mathbf{n} dA \right) \\
&= \text{by divergence theorem} \\
&= \left(-\int_{W} \operatorname{div}(p,0,0) dV, -\int_{W} \operatorname{div}(0,p,0) dV, -\int_{W} \operatorname{div}(0,0,p) dV \right) \\
&= -\int_W (\nabla p) dV
\end{aligned} \tag{39}$$

Now, the total force on the fluid due to the pressure

$$\partial W = -\int_W \nabla p dV \tag{40}$$

If $\mathbf{b}(\mathbf{x}, t)$ denotes the given body force per unit mass (ex: gravity), then the toal body force is

$$F_B = \int_W \rho \cdot \mathbf{b} \cdot dV. \tag{41}$$

By equations (40) and (41), the force per unit volume is $-\nabla p + \rho \mathbf{b}$

By the Newton's second law,

$$\frac{D}{Dt}(\delta m\, \mathbf{u}) = \frac{D}{Dt}(\delta m\, \mathbf{u}(\mathbf{x}, t)) = (-p + \rho \mathbf{b}) \delta V \tag{42}$$

we then have

$$\Rightarrow \rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \rho \mathbf{b} \quad \text{BM1 (Euler equation)} \tag{43}$$

1.2.2 Balance of Momentum 2 (BM2)

WLOG. we write $\mathbf{u}$ for $\mathbf{u} = (u_1, u_2, u_3)$ and b for $\mathbf{b}$, Integral from of balance of momentum

By (BM1)

$$\rho \frac{\partial \mathbf{u}}{\partial t} = -\rho(\mathbf{u} \cdot \nabla)\mathbf{u} - \nabla p + \rho \mathbf{b} \tag{44}$$

then by 44 and continuity equation

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) = \rho_t \mathbf{u} + \rho \mathbf{u}_t = -\operatorname{div}(\rho \mathbf{u})\mathbf{u} - \rho(\mathbf{u} \cdot \nabla)\mathbf{u} - \nabla p + \rho \mathbf{b} \tag{45}$$

Let $\mathbf{e}$ be a fixed vector in space, then

$$\begin{aligned}
\mathbf{e} \cdot \frac{\partial}{\partial t}(\rho \mathbf{u}) &= -\operatorname{div}(\rho \mathbf{u})\mathbf{u} \cdot \mathbf{e} - \rho(\mathbf{u} \cdot \nabla)\mathbf{u} \cdot \mathbf{e} - (\nabla p) \cdot \mathbf{e} + \rho \mathbf{b} \cdot \mathbf{e} \\
&= -\operatorname{div}(\rho \mathbf{u}(\mathbf{u} \cdot \mathbf{e})) - \operatorname{div}(p\mathbf{e}) + \rho \mathbf{b} \cdot \mathbf{e} \\
&= -\operatorname{div}(\rho \mathbf{u}(\mathbf{u} \cdot \mathbf{e}) + p\mathbf{e}) + \rho \mathbf{b} \cdot \mathbf{e}
\end{aligned} \tag{46}$$

Since, we have

1. the divergence of $p\mathbf{e}$

$$
\begin{aligned}
\operatorname{div}(p\mathbf{e}) &= \operatorname{div}\left((pe_1, pe_2, pe_3)\right) \\
&= \frac{\partial p}{\partial x_1}e_1 + \frac{\partial p}{\partial x_2}e_2 + \frac{\partial p}{\partial x_3}e_3 \\
&= \sum_{i=1}^{3} \frac{\partial p}{\partial x_i}e_i = \nabla p \cdot \mathbf{e}
\end{aligned}
\tag{47}
$$

1. the divergence of $\rho\mathbf{u}(\mathbf{u}\cdot\mathbf{e})$

$$
\begin{aligned}
\operatorname{div}(\rho\mathbf{u}(\mathbf{u}\cdot\mathbf{e})) &= \sum_{i=0}^{3} \frac{\partial}{\partial x_i}\left[\rho u_i(\mathbf{u}\cdot\mathbf{e})\right] \\
&= \sum_{i=0}^{3}\left(\frac{\partial}{\partial x_i}(\rho u_i)\right)(\mathbf{u}\cdot\mathbf{e}) + \sum_{i=0}^{3}(\rho u_i)\left(\frac{\partial}{\partial x_i}(\mathbf{u}\cdot\mathbf{e})\right) \\
&= \operatorname{div}(\rho\mathbf{u})(\mathbf{u}\cdot\mathbf{e}) + \rho(\mathbf{u}\cdot\nabla)(\mathbf{u}\cdot\mathbf{e})
\end{aligned}
\tag{48}
$$

Hence, if W is a fixed region in space in the fluid

$$
\begin{aligned}
\mathbf{e}\cdot\frac{d}{dt}\int_W \rho\mathbf{u}dV &= \int_W e\cdot\frac{d}{dt}(\rho\mathbf{u})dV \\
&= -\int_W \operatorname{div}(p\mathbf{e} + \rho\mathbf{u}(\mathbf{u}\cdot\mathbf{e}))dV + \int_W \rho\mathbf{b}\cdot\mathbf{e}dV \\
&= \text{By divergence theorem.} \\
&= -\int_{\partial W}(p\mathbf{e} + \rho\mathbf{u}(\mathbf{u}\cdot\mathbf{e}))\cdot\mathbf{n}dA + \int_W \rho\mathbf{b}\cdot\mathbf{e}dV \\
&= -\int_{\partial W} p\mathbf{e}\cdot\mathbf{n}dA - \int_{\partial W}\rho\mathbf{u}(\mathbf{u}\cdot\mathbf{e})\cdot\mathbf{n}dA + \int_W \rho\mathbf{b}\cdot\mathbf{e}dV, \quad \forall\mathbf{e}\in\mathbb{R}^n, n = 2 \text{ or } 3
\end{aligned}
\tag{49}
$$

then

$$
\frac{d}{dt}\int_W \mathbf{u}dV = -\int_{\partial W} p\mathbf{n}dA - \int_{\partial W}\rho(\mathbf{u}\cdot\mathbf{n})\mathbf{u}dA + \int_{\partial W}\rho\mathbf{b}\cdot\mathbf{e}dV \tag{50}
$$

or

$$
\frac{d}{dt}\int_W \mathbf{u}dV = -\int_{\partial W}\left(p\mathbf{n} + \rho(\mathbf{u}\cdot\mathbf{n})\mathbf{u}\right)dA + \int_{\partial W}\rho\mathbf{b}\cdot\mathbf{e}dV, \quad \text{BM2} \tag{51}
$$

and BM2 is also the Integral form of balance of momentum.

> Note: The quantity $p\mathbf{n} + \rho\mathbf{u}(\mathbf{u}\cdot\mathbf{n})$ is the momentum per unit area crossing ∂W when $\mathbf{n}$ is unit vector outer normal to ∂W.

1.2.3 Balance of Momentum 3 (BM3)

Let D be a region that the fluid is moving and $x \in D$

Let $\varphi(\mathbf{x},t)$ be the trajectory of the partiacle that is at point x, i.e. φ satisfies

$$\begin{aligned} \frac{\partial}{\partial t}\varphi(\mathbf{x},t) &= \mathbf{u}\left(\varphi(\mathbf{x},t),t\right) \quad && \forall t>0 \text{ at time } t \\ \varphi(\mathbf{x},0) &= x && \varphi(\mathbf{x},t)=\varphi_t(\mathbf{x}) \end{aligned} \tag{52}$$

We will assume that φ is smooth and for fixed t, $\varphi_t : t \to \varphi(\mathbf{x},t)$ is invertible.

φ_t doesn't mean $\partial/\partial t$ here!

We called φ is the fluid flow map.

If W is the a region in D, then $W_t := \varphi_t(W)$ is the region of the fluid at time t whose initial position is in W at time t.

Then by the balance of momentum

$$\frac{d}{dt}\int_{W_t} \rho\mathbf{u}dV = \mathbf{F}_{\partial W_t} + \int_{W_t}\rho\mathbf{b}dV, \tag{53}$$

where $\mathbf{F}_{\partial W_t}$ is the force on ∂W_t due to perssure, i.e.

$$\mathbf{F}_{\partial W_t} = -\int_{\partial W_t} p\mathbf{n}dA = -\int_{W_t}\nabla p dV \tag{54}$$

so that

$$\frac{d}{dt}\int_{W_t}\rho\mathbf{u}dV = -\int_{W_t}\nabla p dV + \int_{W_t}\rho\mathbf{b}dV, \quad \text{BM3} \tag{55}$$

Recall

$$\frac{d}{dt}(\delta V) = (\operatorname{div}\mathbf{u})\delta V \tag{56}$$

for an infitesmal volume δV of fluid moving in te fluid with the fluid velocity,
We will now given a rigorous proof of the result.

Now that

$$\begin{aligned} \text{volume}(W_t) &= \int_{W_t} 1 dV \\ &= \int_{W_t} 1 dy, \quad \text{put } y \text{ to be } \varphi_t(\mathbf{x}) \\ &= \int_W J(\mathbf{x},t)d\mathbf{x}, \end{aligned} \tag{57}$$

where $J(\mathbf{x},t)$ is the Jocobian determinant of the map φ_t , so that

$$\frac{d}{dt}\text{volume}(W_t) = \int_W \frac{\partial}{\partial t}J(\mathbf{x},t)d\mathbf{x} \tag{58}$$

1.3 Equivalence between BM1, BM2 and BM3

Quick Summary of *Balance of Momentum*

1. BM1: $\rho\dfrac{D\mathbf{u}}{Dt} = -\nabla p + \rho\mathbf{b}$
2. BM2: $\dfrac{d}{dt}\displaystyle\int_W \rho\mathbf{u}dV = \int_{\partial W}\left(p\mathbf{n} + \rho(\mathbf{u}\cdot\mathbf{n})\mathbf{u}\right)dA + \int_W \rho\mathbf{b}dV$
3. BM3: $\dfrac{d}{dt}\displaystyle\int_{W_t}\rho\mathbf{u}dV = -\int_{W_t}\nabla p dV + \int_{W_t}\rho\mathbf{b}dV$

1.3.1 Lemma

$$\frac{\partial J(\mathbf{x},t)}{\partial t} = \operatorname{div}(\mathbf{u}(y,t)) \cdot J(\mathbf{x},t) \tag{59}$$

1.3.1.1 proof:

$\mathbf{y} = \varphi(\mathbf{x},t) = (y_1, y_2, y_3)$, and $\mathbf{x} = (x_1, x_2, x_3)$. Observe that

$$\frac{\partial \varphi}{\partial t} = \mathbf{u}(\varphi(\mathbf{x},t),t), \quad \text{or} \quad \frac{\partial y_i}{\partial t} = u_i(y,t)\,, \forall i = 1,2,3 \tag{60}$$

then

$$\begin{aligned} J(\mathbf{x},t) &= \operatorname{div}\left(\frac{\partial y_i}{\partial x_j}\right)_{1\le i\le 3} \\ &= \sum_{\sigma\in S} (\operatorname{sign}\sigma)\,\frac{\partial y_1}{\partial x_{\sigma(1)}}\frac{\partial y_2}{\partial x_{\sigma(2)}}\frac{\partial y_3}{\partial x_{\sigma(3)}} \end{aligned} \tag{61}$$

here S is the family of the permutations $\{1,2,3\}$, and

$$\operatorname{sign}\sigma = \begin{cases} 1 & \text{if } \sigma \text{ is an even permutation;} \\ -1 & \text{if } \sigma \text{ is an odd permutation.} \end{cases} \tag{62}$$

then

$$\begin{aligned} \frac{\partial J(\mathbf{x},t)}{\partial t} &= \sum_{\sigma\in S} (\operatorname{sign}\sigma)\,\frac{\partial^2 y_1}{\partial t\partial x_{\sigma(1)}}\frac{\partial y_2}{\partial x_{\sigma(2)}}\frac{\partial y_3}{\partial x_{\sigma(3)}} \\ &\quad + \sum_{\sigma\in S} (\operatorname{sign}\sigma)\,\frac{\partial y_1}{\partial x_{\sigma(1)}}\frac{\partial^2 y_2}{\partial t\partial x_{\sigma(2)}}\frac{\partial y_3}{\partial x_{\sigma(3)}} \\ &\quad + \sum_{\sigma\in S} (\operatorname{sign}\sigma)\,\frac{\partial y_1}{\partial x_{\sigma(1)}}\frac{\partial y_2}{\partial x_{\sigma(2)}}\frac{\partial^2 y_3}{\partial t\partial x_{\sigma(3)}} \\ &= I_1 + I_2 + I_3 \end{aligned} \tag{63}$$

then calculate I_1 first

$$
\begin{aligned}
I_1 &= \sum_{\sigma \in S} (\operatorname{sign} \sigma) \frac{\partial^2 y_1}{\partial t \partial x_{\sigma(1)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \sum_{\sigma \in S} (\operatorname{sign} \sigma) \left(\frac{\partial}{\partial x_{\sigma(2)}} \left(\frac{\partial y_1}{\partial t} \right) \right) \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \sum_{\sigma \in S} (\operatorname{sign} \sigma) \left(\frac{\partial u_1}{\partial x_{\sigma(2)}} \right) \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \sum_{\sigma \in S} (\operatorname{sign} \sigma) \left(\sum_{k=1}^{3} \frac{\partial u_1}{\partial y_k} \frac{\partial y_k}{\partial x_{\sigma(2)}} \right) \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \sum_{\sigma \in S} \sum_{k=1}^{3} (\operatorname{sign} \sigma) \frac{\partial u_1}{\partial y_k} \frac{\partial y_k}{\partial x_{\sigma(2)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \sum_{k=1}^{3} \frac{\partial u_1}{\partial y_k} \sum_{\sigma \in S} (\operatorname{sign} \sigma) \frac{\partial y_k}{\partial x_{\sigma(2)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \frac{\partial u_1}{\partial y_1} \sum_{\sigma \in S} (\operatorname{sign} \sigma) \frac{\partial y_1}{\partial x_{\sigma(2)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&\quad + \frac{\partial u_1}{\partial y_2} \sum_{\sigma \in S} (\operatorname{sign} \sigma) \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&\quad + \frac{\partial u_1}{\partial y_3} \sum_{\sigma \in S} (\operatorname{sign} \sigma) \frac{\partial y_3}{\partial x_{\sigma(2)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} \\
&= \frac{\partial u_1}{\partial y_1} \sum_{\sigma \in S} (\operatorname{sign} \sigma) \frac{\partial y_1}{\partial x_{\sigma(2)}} \frac{\partial y_2}{\partial x_{\sigma(2)}} \frac{\partial y_3}{\partial x_{\sigma(3)}} + 0 + 0 \\
&= \frac{\partial u_1}{\partial y_1} J(\mathbf{x}, t)
\end{aligned}
\tag{64}
$$

using the same we can get

$$
\begin{aligned}
\frac{\partial J(\mathbf{x}, t)}{\partial t} &= I_1 + I_2 + I_3 \\
&= \frac{\partial u_1}{\partial y_1} J(\mathbf{x}, t) + \frac{\partial u_2}{\partial y_2} J(\mathbf{x}, t) + \frac{\partial u_3}{\partial y_3} J(\mathbf{x}, t) \\
&= \left(\sum_{i=1}^{3} \frac{\partial u_i}{\partial y_i} \right) J(\mathbf{x}, t) \\
&= \operatorname{div}_y (\mathbf{u}) \, J(\mathbf{x}, t)
\end{aligned}
\tag{65}
$$

1.3.2 Transport Theorem

For any smooth function $f : D \times [0, T] \to \mathbb{R}$, we have

$$
\frac{d}{dt} \int_{W_t} \rho f \, dV_y = \int_{W_t} \rho \frac{Df}{dt} \, dV_y \tag{66}
$$

1.3.2.1 proof

Change $W_t \to W$

$$\int_{W_t} \rho f dV_y = \int_W \rho(\varphi(\mathbf{x},t),t) f(\varphi(\mathbf{x},t),t) J(\mathbf{x},t)\, dx \tag{67}$$

we have

$$\begin{aligned}
\frac{d}{dt}\int_{W_t} \rho f dV &= \frac{d}{dt}\int_W \rho(\varphi(\mathbf{x},t),t) f(\varphi(\mathbf{x},t),t) J(\mathbf{x},t)\, dx \\
&= \int_W \frac{d}{dt}\Big(\rho(\varphi(\mathbf{x},t),t) f(\varphi(\mathbf{x},t),t) J(\mathbf{x},t)\Big)\, dx \\
&= \int_W \frac{d}{dt}\Big(\rho(y,t) f(y,t) J(\mathbf{x},t)\Big)\, dx \\
&= \int_W \frac{d}{dt}\Big(\rho(y,t) f(y,t)\Big) J(\mathbf{x},t)\, dx + \int_W \rho(y,t) f(y,t) \frac{d}{dt}\Big(J(\mathbf{x},t)\Big)\, dx \\
&= \int_W \frac{d}{dt}\left(\rho f\right) J(\mathbf{x},t)\, dx + \int_W (\rho f)\operatorname{div}_y(\mathbf{u}) J(\mathbf{x},t)\, dx \\
&= \int_W \left(\frac{d}{dt}\left(\rho f\right) + (\rho f)\operatorname{div}_y(\mathbf{u}) J(\mathbf{x},t)\right)\, dx \\
&= \int_W \left(\frac{\partial}{\partial t}(\rho f) + \nabla_y(\rho f)\cdot\left(\frac{dy}{dt}\right) + (\rho f)\operatorname{div}_y(\mathbf{u})\right) J(\mathbf{x},t)\, dx \\
&= \int_W \left(\frac{\partial}{\partial t}(\rho f) + \nabla_y(\rho f)\cdot\mathbf{u} + (\rho f)\operatorname{div}_y(\mathbf{u})\right) J(\mathbf{x},t)\, dx \\
&= \int_W \left(\frac{D(\rho f)}{Dt} + (\rho f)\operatorname{div}_y(\mathbf{u})\right) J(\mathbf{x},t)\, dx \\
&= \int_W \left(\frac{D(\rho f)}{Dt} + (\rho f)\operatorname{div}_y(\mathbf{u})\right) dV_y
\end{aligned} \tag{68}$$

and consider the first term in the integral

$$
\begin{aligned}
\frac{D(\rho f)}{Dt} &= \frac{\partial(\rho f)}{\partial t} + \mathbf{u}\cdot\nabla_y(\rho f) \\
&= f\frac{\partial\rho}{\partial t} + \rho\frac{\partial f}{\partial t} + \mathbf{u}\cdot(f\,\nabla_y\rho + \rho\,\nabla_y f) \\
&= f\left(\frac{\partial\rho}{\partial t} + \mathbf{u}\cdot\nabla_y\rho\right) + \rho\left(\frac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla_y f\right) \\
&= f\Big(\rho_t + \mathbf{u}\cdot\nabla_y\rho\Big) + \rho\Big(f_t + \mathbf{u}\cdot\nabla_y f\Big) \\
&= f\Big(\rho_t + \operatorname{div}(\rho\mathbf{u}) - \rho\operatorname{div}(\mathbf{u})\Big) + \rho\Big(f_t + \mathbf{u}\cdot\nabla_y f\Big) \\
&= f\underbrace{\Big(\rho_t + \operatorname{div}(\rho\mathbf{u})\Big)}_{\text{continuity equation}=0} - f\rho\operatorname{div}(\mathbf{u}) + \rho\Big(f_t + \mathbf{u}\cdot\nabla_y f\Big) \\
&= -f\rho\operatorname{div}(\mathbf{u}) + \rho\Big(f_t + \mathbf{u}\cdot\nabla_y f\Big) \\
&= \rho\Big(f_t + \mathbf{u}\cdot\nabla_y f\Big) - \rho f\operatorname{div}(\mathbf{u}) \\
&= \rho\frac{Df}{Dt} - (\rho f)\operatorname{div}(\mathbf{u})
\end{aligned} \tag{69}
$$

then plugin to the integral

$$
\begin{aligned}
\frac{d}{dt}\int_{W_t}\rho f dV &= \int_W \left(\frac{D(\rho f)}{Dt} + (\rho f)\operatorname{div}_y(\mathbf{u})\right) dV \\
&= \int_W \left(\rho\frac{Df}{Dt} - (\rho f)\operatorname{div}(\mathbf{u}) + (\rho f)\operatorname{div}_y(\mathbf{u})\right) dV \\
&= \int_W \left(\rho\frac{Df}{Dt}\right) dV
\end{aligned} \tag{70}
$$

we get

$$
\frac{d}{dt}\int_{W_t}\rho f dV = \int_W \left(\rho\frac{Df}{Dt}\right) dV, \quad \forall f \text{ is smooth function} \tag{71}
$$

Notice that:

$$
\frac{d}{dt}\int_{W_t}\rho f dV = \int_W \left(\rho\frac{Df}{Dt}\right) dV \tag{72}
$$

so when we consider a vector fucntion $\mathbf{u}$, we can write

$$\begin{aligned}
\frac{d}{dt}\int_{W_t} \rho \mathbf{u} dV &= \frac{d}{dt}\int_{W_t} \rho(u_1, u_2, u_3) dV \\
&= \left(\frac{d}{dt}\int_{W_t} \rho u_1 dV, \frac{d}{dt}\int_{W_t} \rho u_2 dV, \frac{d}{dt}\int_{W_t} \rho u_3 dV\right) \\
&= \left(\int_W \left(\rho \frac{Du_1}{Dt}\right) dV, \int_W \left(\rho \frac{Du_2}{Dt}\right) dV, \int_W \left(\rho \frac{Du_3}{Dt}\right) dV\right) \\
&= \int_W \left(\rho \frac{Du_1}{Dt}, \rho \frac{Du_2}{Dt} \rho \frac{Du_3}{Dt}\right) dV \\
&= \int_W \rho \frac{D}{Dt} (u_1, u_2, u_3)\ dV \\
&= \int_W \rho \frac{D\mathbf{u}}{Dt} dV
\end{aligned} \tag{73}$$

Now we rewrite BM3

$$\frac{d}{dt}\int_{W_t} \rho \mathbf{u} dV = -\int_{W_t} \nabla p dV + \int_{W_t} \rho \mathbf{b} dV \tag{74}$$

to be

$$\frac{d}{dt}\int_{W_t} \rho \mathbf{u} dV + \int_{W_t} \nabla p dV - \int_{W_t} \rho \mathbf{b} dV = 0 \tag{75}$$

then using the result from above

$$\begin{aligned}
0 &= \frac{d}{dt}\int_{W_t} \rho \mathbf{u} dV + \int_{W_t} \nabla p dV - \int_{W_t} \rho \mathbf{b} dV \\
0 &= \int_{W_t} \rho \frac{D\mathbf{u}}{Dt} dV + \int_{W_t} \nabla p dV - \int_{W_t} \rho \mathbf{b} dV \\
0 &= \int_{W_t} \left(\rho \frac{D\mathbf{u}}{Dt} dV + \nabla p dV - \rho \mathbf{b}\right) dV, \quad \forall W_t
\end{aligned} \tag{76}$$

imply

$$\rho \frac{D\mathbf{u}}{Dt} dV + \nabla p dV - \rho \mathbf{b} = 0 \tag{77}$$

which is just BM1, this means BM3 is equivalent to BM1.

Similarly,

$$\frac{d}{dt}\int_W \rho \mathbf{u} dV = \int_{\partial W_t} p\mathbf{n} + \rho(\mathbf{u}\cdot\mathbf{n})\mathbf{u} dA + \int_W \rho \mathbf{b} dV \tag{78}$$

so that

$$\text{BM1} \Leftrightarrow \text{BM2} \Leftrightarrow \text{BM3} \tag{79}$$

By an arrgument similart ot the proof of the transport theorem, for any smooth function $f : D \times [0, T] \to \mathbb{R}$, we have

$$\frac{d}{dt}\left(\int_{W_t} f dV\right) = \int_{W_t} \left(\frac{Df}{Dt} + f(\operatorname{div}\mathbf{u})\right) dV \tag{80}$$

or in the other form as the textbook

$$\frac{d}{dt}\int_{W_t} f dV = \int_{W_t} \left(\frac{\partial f}{\partial t} + \operatorname{div}(f\mathbf{u})\right) dV, \tag{81}$$

since $\dfrac{Df}{Dt} = \dfrac{\partial f}{\partial t} + \mathbf{u}\cdot\nabla f$, and these 2 equations (80) and (81) is called the *Transport theorem without mass density.*

Rmk: Here we consider the *Transport theorem* (with mass density):

$$\frac{d}{dt}\int_{W_t} \rho f dV = \int_{W_t} \rho\frac{Df}{Dt} dV, \tag{82}$$

if we take ρ to be a constant (ex: $\rho = 1$), we have

$$\frac{d}{dt}\int_{W_t} f dV = \int_{W_t} \frac{Df}{Dt} dV, \tag{83}$$

however compare to the equation without no mass density (80),

$$\frac{d}{dt}\left(\int_{W_t} f dV\right) = \int_{W_t} \frac{Df}{Dt} dV + \int_{W_t} f(\operatorname{div}\mathbf{u}) dV \tag{84}$$

we have an extra term contain $f(\operatorname{div}\mathbf{u})$. **BUT**, if we consider more carefully, the mass density ρ here must satisfy the continuity equation, i.e.

$$\rho_t + \operatorname{div}(\rho\mathbf{u}) = 0 \tag{85}$$

so that if mass density is a constant (ex: $\rho = 1$), we have

$$\rho_t + \operatorname{div}(\rho\mathbf{u}) = 0 + \operatorname{div}(\mathbf{u}) = 0 \tag{86}$$

so that $\operatorname{div}\mathbf{u} = 0$, which means the extra term vanishing, and the *transport theorem with mass density* and *transport theorem without mass density* are equivalent.