PHY 711 Classical Mechanics and Mathematical Methods
10-10:50 AM MWF Olin 103

Plan for Lecture 35

Viscous fluids – Chap. 12 in F & W

1. **Viscous stress tensor**
2. **Navier-Stokes equation**
3. **Example for incompressible fluid**

21	Fri, 10/19/2018	Chap. 7	Laplace transforms; Contour integrals	#13	10/24/2018
22	Mon, 10/22/2018	Chap. 7	Contour integrals		
23	Wed, 10/24/2018	Chap. 5	Rigid body motion	#14	10/26/2018
24	Fri, 10/26/2018	Chap. 5	Rigid body motion	#15	10/31/2018
25	Mon, 10/29/2018	Chap. 8	Mechanics of elastic membranes	#16	11/02/2018
26	Wed, 10/31/2018	Chap. 9	Mechanics of three dimensional fluids		
27	Fri, 11/02/2018	Chap. 9	Mechanics of fluids	#17	11/07/2018
28	Mon, 11/05/2018	Chap. 9	Sound waves	Project topic	
29	Wed, 11/07/2018	Chap. 9	Sound waves	#18	11/12/2018
30	Fri, 11/09/2018	Chap. 9	Linear and non-linear sound		
31	Mon, 11/12/2018	Chap. 10	Surface waves	#19	11/16/2018
32	Wed, 11/14/2018	Chap. 10	Surface waves -- nonlinear effects		
33	Fri, 11/16/2018	Chap. 11	Heat conductivity	#20	11/26/2018
34	Mon, 11/19/2018	Chap. 13	Elastic media		
	Wed, 11/21/2018	No class	Thanksgiving holiday		
	Fri, 11/23/2018	No class	Thanksgiving holiday		
35	Mon, 11/26/2018	Chap. 12	Viscous fluids		
36	Wed, 11/28/2018	Chap. 12	Viscous fluids		
37	Fri, 11/30/2018		Review		
	Mon, 12/03/2018		Presentations I		
	Wed, 12/05/2018		Presentations II		
	Fri, 12/07/2018		Presentations III		

Signup for presentation times immediately after class (watch for email with link)

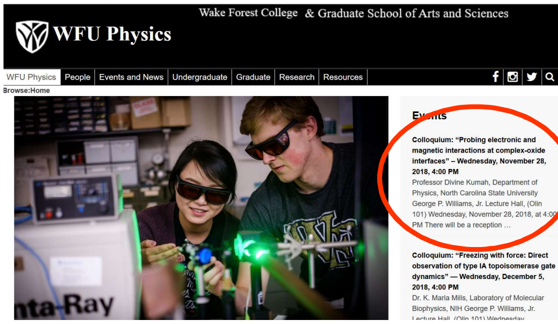
PHY 711 Presentation Schedule for Fall 2018

Monday December 3, 2018

	Name	Topic
10-10:25		
10:25-10:50		

Wednesday December 5, 2018

	Name	Topic
10-10:15		
10:15-10:30		
10:30-10:45		



Equations for motion of non-viscous fluid

Newton-Euler equation of motion:

$$\rho\frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v}\cdot\nabla)\mathbf{v} = \rho\mathbf{f}_{applied} - \nabla p$$

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0 \qquad \Rightarrow \mathbf{v}\left(\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v})\right) = 0$$

Add two equations:

$$\underbrace{\rho\frac{\partial \mathbf{v}}{\partial t} + \frac{\partial \rho}{\partial t}\mathbf{v}}_{\frac{\partial(\rho\mathbf{v})}{\partial t}} + \underbrace{\rho(\mathbf{v}\cdot\nabla)\mathbf{v} + \mathbf{v}\nabla\cdot(\rho\mathbf{v})}_{\sum_{j=1}^{3}\frac{\partial(\rho v_j \mathbf{v})}{\partial x_j}} = \rho\mathbf{f}_{applied} - \nabla p$$

Equations for motion of non-viscous fluid -- continued

Newton-Euler equation in terms of momentum:

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \sum_{j=1}^{3}\frac{\partial(\rho v_j \mathbf{v})}{\partial x_j} = \rho\mathbf{f}_{applied} - \nabla p$$

$$\frac{\partial(\rho\mathbf{v})}{\partial t} + \sum_{j=1}^{3}\frac{\partial(\rho v_j \mathbf{v})}{\partial x_j} + \nabla p = \rho\mathbf{f}_{applied}$$

Fluid momentum: $\rho\mathbf{v}$

Stress tensor: $T_{ij} \equiv \rho v_i v_j + p\delta_{ij}$

i^{th} component of Newton-Euler equation:

$$\frac{\partial(\rho v_i)}{\partial t} + \sum_{i=1}^{3}\frac{\partial T_{ij}}{\partial x_j} = \rho f_i$$

Now consider the effects of viscosity

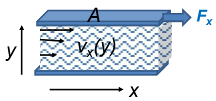
In terms of stress tensor:

$$T_{ij} = T_{ij}^{\text{ideal}} + T_{ij}^{\text{viscous}}$$

$$T_{ij}^{\text{ideal}} = \rho v_i v_j + p\delta_{ij} = T_{ji}^{\text{ideal}}$$

Newton's "law" of viscosity

$$\frac{F_x}{A} = \eta \frac{\partial v_x}{\partial y}$$



Effects of viscosity

Argue that viscosity is due to shear forces in a fluid of the form:

$$\frac{F_{drag}}{A} = \eta \frac{\partial v_x}{\partial y}$$

Formulate viscosity stress tensor with traceless and diagonal terms:

$$T_{kl}^{\text{viscous}} = -\eta\left(\frac{\partial v_k}{\partial x_l} + \frac{\partial v_l}{\partial x_k} - \frac{2}{3}\delta_{kl}(\nabla\cdot\mathbf{v})\right) - \zeta\delta_{kl}(\nabla\cdot\mathbf{v})$$

viscosity   bulk viscosity

Total stress tensor: $T_{kl} = T_{kl}^{ideal} + T_{kl}^{\text{viscous}}$

$$T_{kl}^{\text{ideal}} = \rho v_k v_l + p\delta_{kl}$$

$$T_{kl}^{\text{viscous}} = -\eta\left(\frac{\partial v_k}{\partial x_l} + \frac{\partial v_l}{\partial x_k} - \frac{2}{3}\delta_{kl}(\nabla\cdot\mathbf{v})\right) - \zeta\delta_{kl}(\nabla\cdot\mathbf{v})$$

Effects of viscosity -- continued

Incorporating generalized stress tensor into Newton-Euler equations

$$\frac{\partial(\rho v_i)}{\partial t} + \sum_{i=1}^{3}\frac{\partial T_{ij}}{\partial x_j} = \rho f_i$$

$$\frac{\partial(\rho v_i)}{\partial t} + \sum_{j=1}^{3}\frac{\partial(\rho v_i v_j)}{\partial x_j} = \rho f_i - \frac{\partial p}{\partial x_i} + \eta\sum_{j=1}^{3}\frac{\partial^2 v_i}{\partial x_j^2} + \left(\zeta + \frac{1}{3}\eta\right)\sum_{j=1}^{3}\frac{\partial^2 v_j}{\partial x_i \partial x_j}$$

Continuity condition

$$\frac{\partial \rho}{\partial t} + \sum_{j=1}^{3}\frac{\partial(\rho v_j)}{\partial x_j} = 0$$

Vector form (Navier-Stokes equation)

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = \mathbf{f} - \frac{1}{\rho}\nabla p + \frac{\eta}{\rho}\nabla^2\mathbf{v} + \frac{1}{\rho}\left(\zeta + \frac{1}{3}\eta\right)\nabla(\nabla\cdot\mathbf{v})$$

Continuity condition

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

Newton-Euler equations for viscous fluids

Navier-Stokes equation

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = \mathbf{f} - \frac{1}{\rho}\nabla p + \frac{\eta}{\rho}\nabla^2\mathbf{v} + \frac{1}{\rho}\left(\zeta + \frac{1}{3}\eta\right)\nabla(\nabla\cdot\mathbf{v})$$

Continuity condition

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

Typical viscosities at 20° C and 1 atm:

Fluid	η/ρ (m^2/s)	η (Pa s)
Water	1.00 x 10^{-6}	1 x 10^{-3}
Air	14.9 x 10^{-6}	0.018 x 10^{-3}
Ethyl alcohol	1.52 x 10^{-6}	1.2 x 10^{-3}
Glycerine	1183 x 10^{-6}	1490 x 10^{-3}

Example – steady flow of an incompressible fluid in a long pipe with a circular cross section of radius *R*

Navier-Stokes equation

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = \mathbf{f} - \frac{1}{\rho}\nabla p + \frac{\eta}{\rho}\nabla^2\mathbf{v} + \frac{1}{\rho}\left(\zeta + \frac{1}{3}\eta\right)\nabla(\nabla\cdot\mathbf{v})$$

Continuity condition

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\mathbf{v}) = 0$$

Note that $\nabla\times(\nabla\times\mathbf{v}) = \nabla(\nabla\cdot\mathbf{v}) - \nabla^2\mathbf{v}$

Incompressible fluid $\Rightarrow$ $\nabla\cdot\mathbf{v} = 0$

Steady flow $\Rightarrow$ $\frac{\partial \mathbf{v}}{\partial t} = 0$

Irrotational flow $\Rightarrow$ $\nabla\times\mathbf{v} = 0$

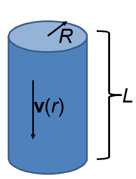
No applied force $\Rightarrow$ $\mathbf{f}=0$

Neglect non-linear terms $\Rightarrow \nabla(v^2) = 0$

Example – steady flow of an incompressible fluid in a long pipe with a circular cross section of radius *R* -- continued

Navier-Stokes equation becomes:

$$0 = -\frac{1}{\rho}\nabla p + \frac{\eta}{\rho}\nabla^2\mathbf{v}$$



Assume that $\mathbf{v}(\mathbf{r},t) = v_z(r)\hat{\mathbf{z}}$

$$\frac{\partial p}{\partial z} = \eta\nabla^2 v_z(r) \quad \text{(independent of } z\text{)}$$

Suppose that $\frac{\partial p}{\partial z} = -\frac{\Delta p}{L}$ (uniform pressure gradient)

$$\Rightarrow \nabla^2 v_z(r) = -\frac{\Delta p}{\eta L}$$

Example – steady flow of an incompressible fluid in a long pipe with a circular cross section of radius *R* -- continued

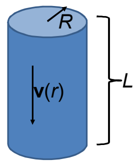
$$\nabla^2 v_z(r) = -\frac{\Delta p}{\eta L}$$

$$\frac{1}{r}\frac{d}{dr} r \frac{dv_z(r)}{dr} = -\frac{\Delta p}{\eta L}$$

$$v_z(r) = -\frac{\Delta p r^2}{4\eta L} + C_1 \ln(r) + C_2$$

$$\Rightarrow C_1 = 0 \qquad v_z(R) = 0 = -\frac{\Delta p R^2}{4\eta L} + C_2$$

$$v_z(r) = \frac{\Delta p}{4\eta L}\left(R^2 - r^2\right)$$

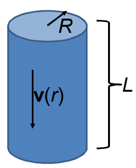


Example – steady flow of an incompressible fluid in a long pipe with a circular cross section of radius *R* -- continued

$$v_z(r) = \frac{\Delta p}{4\eta L}\left(R^2 - r^2\right)$$

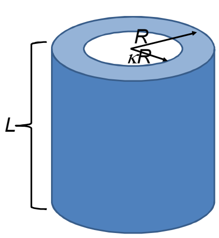
Mass flow rate through the pipe:

$$\frac{dM}{dt} = 2\pi\rho \int_0^R r dr v_z(r) = \frac{\Delta p \rho \pi R^4}{8\eta L}$$



Poiseuille formula;
➔Method for measuring η

Example – steady flow of an incompressible fluid in a long tube with a circular cross section of outer radius *R* and inner radius *κR*



$$\nabla^2 v_z(r) = -\frac{\Delta p}{\eta L}$$

$$\frac{1}{r}\frac{d}{dr} r \frac{dv_z(r)}{dr} = -\frac{\Delta p}{\eta L}$$

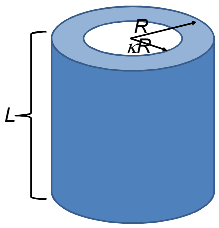
$$v_z(r) = -\frac{\Delta p r^2}{4\eta L} + C_1 \ln(r) + C_2$$

$$v_z(R) = 0 = -\frac{\Delta p R^2}{4\eta L} + C_1 \ln(R) + C_2$$

$$v_z(\kappa R) = 0 = -\frac{\Delta p \kappa^2 R^2}{4\eta L} + C_1 \ln(\kappa R) + C_2$$

Example – steady flow of an incompressible fluid in a long tube with a circular cross section of outer radius R and inner radius κR -- continued

Solving for C_1 and C_2 :



$$v_z(r) = \frac{\Delta p R^2}{4\eta L}\left(1-\left(\frac{r}{R}\right)^2 - \frac{1-\kappa^2}{\ln\kappa}\ln\left(\frac{r}{R}\right)\right)$$

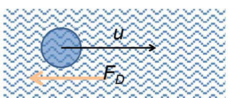
Mass flow rate through the pipe:

$$\frac{dM}{dt} = 2\pi\rho\int_{\kappa R}^{R} r dr v_z(r) = \frac{\Delta p \rho \pi R^4}{8\eta L}\left(1-\kappa^4 + \frac{\left(1-\kappa^2\right)^2}{\ln\kappa}\right)$$

More discussion of viscous effects in incompressible fluids

Stokes' analysis of viscous drag on a sphere of radius R moving at speed u in medium with viscosity η :

$$F_D = -\eta\left(6\pi R u\right)$$



Plan:

1. Consider the general effects of viscosity on fluid equations
2. Consider the solution to the linearized equations for the case of steady-state flow of a sphere of radius R
3. Infer the drag force needed to maintain the steady-state flow

Newton-Euler equation for incompressible fluid, modified by viscous contribution (Navier-Stokes equation):

$$\frac{\partial \mathbf{v}}{\partial t} + \left(\mathbf{v}\cdot\nabla\right)\mathbf{v} = \mathbf{f}_{applied} - \frac{\nabla p}{\rho} + \underbrace{\frac{\eta}{\rho}}_{\upsilon}\nabla^2\mathbf{v}$$

υ Kinematic viscosity

Typical kinematic viscosities at 20° C and 1 atm:

Fluid	ν (m²/s)
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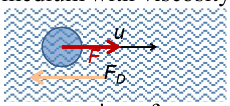

Effects of drag force on motion of particle of mass m with constant force F :

$$F - 6\pi R\eta u = m\frac{du}{dt} \qquad \text{with } u(0) = 0$$

$$\Rightarrow u(t) = \frac{F}{6\pi R\eta}\left(1 - e^{-\frac{6\pi R\eta}{m}t}\right)$$

Effects of drag force on motion of particle of mass m with constant force F :

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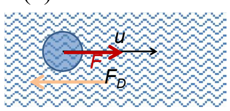
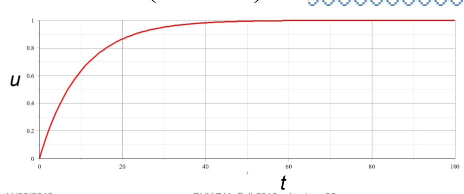
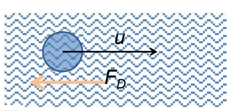


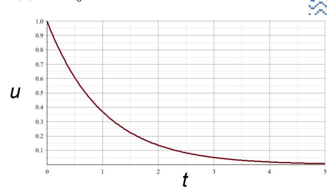


Effects of drag force on motion of particle of mass m with an initial velocity with $u(0) = U_0$ and no external force

$$-6\pi R\eta u = m\frac{du}{dt}$$

$$\Rightarrow u(t) = U_0 e^{-\frac{6\pi R\eta}{m}t}$$



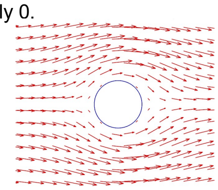


Recall: PHY 711 -- Assignment #17 Nov. 2, 2018

Determine the form of the velocity potential for an incompressible fluid representing uniform velocity in the **z** direction at large distances from a spherical obstruction of radius *a*. Find the form of the velocity potential and the velocity field for all *r* > *a*. Assume that for *r* = *a*, the velocity in the radial direction is 0 but the velocity in the azimuthal direction is not necessarily 0.

$$\nabla^2\Phi = 0$$

$$\Phi(r,\theta) = -v_0\left(r + \frac{a^3}{2r^2}\right)\cos\theta$$



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Newton-Euler equation for incompressible fluid, modified by viscous contribution (Navier-Stokes equation):

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v}\cdot\nabla)\mathbf{v} = \mathbf{f}_{applied} - \frac{\nabla p}{\rho} + \frac{\eta}{\rho}\nabla^2\mathbf{v}$$

Continuity equation: $\nabla\cdot\mathbf{v} = 0$

Assume steady state: $\Rightarrow \frac{\partial \mathbf{v}}{\partial t} = 0$

Assume non-linear effects small

Initially set $\mathbf{f}_{applied} = 0$;

$$\Rightarrow \nabla p = \eta\nabla^2\mathbf{v}$$

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$$\nabla p = \eta\nabla^2\mathbf{v}$$

Take curl of both sides of equation:

$$\nabla\times(\nabla p) = 0 = \eta\nabla^2(\nabla\times\mathbf{v})$$

Assume (with a little insight from Landau):

$$\mathbf{v} = \nabla\times(\nabla\times f(r)\mathbf{u}) + \mathbf{u}$$

where $f(r)\xrightarrow[r\to\infty]{} 0$

Note that:

$$\nabla\times(\nabla\times\mathbf{A}) = \nabla(\nabla\cdot\mathbf{A}) - \nabla^2\mathbf{A}$$

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Digression

Some comment on assumption: $\mathbf{v} = \nabla \times \left(\nabla \times f(r)\mathbf{u}\right) + \mathbf{u}$

$\nabla \times \left(\nabla \times \mathbf{A}\right) = \nabla\left(\nabla \cdot \mathbf{A}\right) - \nabla^2 \mathbf{A}$

Here $\mathbf{A} = f(r)\mathbf{u}$

$\nabla \times \mathbf{v} = \nabla \times \left(\nabla \times \left(\nabla \times \mathbf{A}\right)\right) = -\nabla \times \left(\nabla^2 \mathbf{A}\right)$

Also note: $\nabla p = \eta \nabla^2 \mathbf{v}$

$\Rightarrow \nabla \times \nabla p = \nabla \times \eta \nabla^2 \mathbf{v}$ or $\nabla^2\left(\nabla \times \mathbf{v}\right) = 0$

$$\mathbf{v} = \nabla \times \left(\nabla \times f(r)\mathbf{u}\right) + \mathbf{u}$$

$$\mathbf{u} = u\hat{\mathbf{z}}$$

$$\nabla \times \left(\nabla \times f(r)\hat{\mathbf{z}}\right) = \nabla\left(\nabla \cdot f(r)\hat{\mathbf{z}}\right) - \nabla^2 f(r)\hat{\mathbf{z}}$$

$$\nabla \times \mathbf{v} = 0 \qquad \Rightarrow \nabla^2\left(\nabla \times \mathbf{v}\right) = 0$$

$$\nabla^4\left(\nabla \times f(r)\hat{\mathbf{z}}\right) = 0 \qquad \Rightarrow \nabla^4\left(\nabla f(r) \times \hat{\mathbf{z}}\right) = 0 \qquad \Rightarrow \nabla^4 f(r) = 0$$

$$f(r) = C_1 r^2 + C_2 r + C_3 + \frac{C_4}{r}$$

$$v_r = u\cos\theta\left(1 - \frac{2}{r}\frac{df}{dr}\right) = u\cos\theta\left(1 - 4C_1 - \frac{2C_2}{r} + \frac{2C_4}{r^3}\right)$$

$$v_\theta = -u\sin\theta\left(1 - \frac{d^2 f}{dr^2} - \frac{1}{r}\frac{df}{dr}\right) = -u\sin\theta\left(1 - 4C_1 - \frac{C_2}{r} - \frac{C_4}{r^3}\right)$$

Some details:

$$\nabla^4 f(r) = 0 \qquad \Rightarrow \left(\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr}\right)^2 f(r) = 0$$

$$f(r) = C_1 r^2 + C_2 r + C_3 + \frac{C_4}{r}$$

$$\mathbf{v} = u\left(\nabla \times \left(\nabla \times f(r)\hat{\mathbf{z}}\right) + \hat{\mathbf{z}}\right)$$

$$= u\left(\nabla\left(\nabla \cdot \left(f(r)\hat{\mathbf{z}}\right)\right) - \nabla^2 f(r)\hat{\mathbf{z}} + \hat{\mathbf{z}}\right)$$

Note that: $\hat{\mathbf{z}} = \cos\theta\hat{\mathbf{r}} - \sin\theta\hat{\boldsymbol{\theta}}$

$$\mathbf{v} = u\left(\nabla\left(\frac{df}{dr}\cos\theta\right) - \left(\nabla^2\left(f(r)\right) - 1\right)\left(\cos\theta\hat{\mathbf{r}} - \sin\theta\hat{\boldsymbol{\theta}}\right)\right)$$

$$v_r = u\cos\theta\left(1-\frac{2}{r}\frac{df}{dr}\right) = u\cos\theta\left(1-4C_1-\frac{2C_2}{r}+\frac{2C_4}{r^3}\right)$$

$$v_\theta = -u\sin\theta\left(1-\frac{d^2 f}{dr^2}-\frac{1}{r}\frac{df}{dr}\right) = -u\sin\theta\left(1-4C_1-\frac{C_2}{r}-\frac{C_4}{r^3}\right)$$

To satisfy $\mathbf{v}(r\to\infty)=\mathbf{u}$: $\Rightarrow C_1 = 0$

To satisfy $\mathbf{v}(R)=0$ solve for C_2, C_4

$$v_r = u\cos\theta\left(1-\frac{3R}{2r}+\frac{R^3}{2r^3}\right)$$

$$v_\theta = -u\sin\theta\left(1-\frac{3R}{4r}-\frac{R^3}{4r^3}\right)$$

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$$v_r = u\cos\theta\left(1-\frac{3R}{2r}+\frac{R^3}{2r^3}\right)$$

$$v_\theta = -u\sin\theta\left(1-\frac{3R}{4r}-\frac{R^3}{4r^3}\right)$$

Determining pressure:

$$\nabla p = \eta\nabla^2\mathbf{v} = -\eta\nabla\left(u\cos\theta\left(\frac{3R}{2r^2}\right)\right)$$

$$\Rightarrow p = p_0 - \eta u\cos\theta\left(\frac{3R}{2r^2}\right)$$

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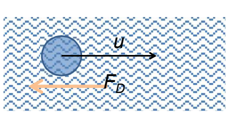
$$p = p_0 - \eta u\cos\theta\left(\frac{3R}{2r^2}\right)$$

Corresponds to:

$$F_D\cos\theta = \left(p(R)-p_0\right)4\pi R^2$$

$$\Rightarrow F_D = -\eta u\left(6\pi R\right)$$



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