Paper Experimental Study of Smoke over a Backward-facing Step Geometry

by Steven Darmawan

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EXPERIMENTAL STUDY OF SMOKE OVER A BACKWARD-FACING STEP GEOMETRY

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Abstract

Separated flows occur in many engineering application such as in airfoils, car tail, around building, etc. and often lead to swirling flow and reattachment. Backward-facing step geometry is widely used for analyzing separated flow as well as swirling flow that usually attached. There are numbers of papers published involving backward-facing step (BFS) geometry experimentally and numerically. Its simple geometry provides a lot of flow information also make BFS geometry even often use to validate turbulence model in numerical (CFD) method and turbulent flow since few last decades. Unfortunately, most experimental setup to describe flows of a BFS are costly, involving high tech equipment. Moreover, separated and swirling flows on BFS which undoubtedly a turbulent flow also make this geometry used as heat transfer benchmark.This paper aim is to develop a low-cost experimental research for visualizing the separated and swirling flows of acrylic-based BFS geometry using smoke as the working fluid as well as temperature effect on the flow. Acrylic-based BFS is manufactured with 5 points temperature measurement. Smoke is use as the working fluid with inlet Reynolds number of 14.631. The separated and swirling flow captured by a low-cost HD video recording, temperature along the BFS is acquired. Prandtl number is used to describe viscosity and diffusivity. The separated and swirling flows is occurred at x/h = 1,02 or 42mm form the expansion zone. The measured temperature is decreasing at the expansion zone which confirmed by the calculated Prandtl number which increase. This result indicates that the viscosity is affect the flow more than the thermal diffusivity.

Keywords: Backward-facing step geometry, separated and swirling flows, Prandtl number

1. INTRODUCTION

Separated flows occur in many engineering application such as in airfoils, car tail, around building, etc. In some cases, separated flows often lead to swirling flow and reattachment [1], [2]. Backward-facing step geometry is widely used for analyzing separated flow as well as swirling flow that usually attached [3] [4]. There are numbers of papers published involving backward-facing step (BFS) geometry, experimentally and numerically. Unfortunately, most experimental setup to describe flows of a BFS are costly, involving high tech equipment [5], [6]Its simple geometry provides a lot of flow information also make BFS geometry often use to validate turbulence model in numerical (CFD) method and turbulent flow since few last decades. Sarker et.al use computational method to analyse flow on the BFS [7]. Thangam et.al and Anwar-ul-Haque et.al use BFS to evaluate the performance of turbulence model [8], [9], [10]. Hossain et.al use BFS to investigate the flow over a BFS [11]. Deatiled numerical method also requires high computer specification [12].

Separated and swirling flows on BFS which undoubtedly a turbulent flow also make this geometry used as heat transfer benchmark as done by Ramsak and Kanna particularly the relationship of the swirling flows, reattachment length to the heat transfer references such as Prandtl number and Nusselt number [13], [14].

In turbulent flow, fluctuating velocity in cascade energy will be dissipated as heat in a convective way if there are no external forces. Despite this convective transport effect is dominant, the molecular transport represented by temperature difference still affect the flow behavior because turbulence transport heat just as rapidly as momentum [15].

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Therefore, the effect of separated and swirling flows in temperature need to be defined, such as by Prandtl number which correlates viscosity and diffusivity [16].

On the other side, the cost of experimental research on turbulent flow become obstacles on many research to be done appropriately and continuously. This paper aim is to develop a low-cost experimental research for visualizing the separated and swirling flows of acrylic-based BFS geometry using smoke as the working fluid and how the swirling flow affect the temperature inside the BFS.

2. RESEARCH METHOD

A. BFS Geometry

The BS geometry design is based on numbers of parameters; step height *(h),* upstream height *(H),* expansion ratio, and total length (*L*). The expansion ratio is defined as (*(H+h)/H*). With 20*h* width. As already known, there is no general value the BFS geometry parameters [17]. Based on that assumption, this paper adapt most of BFS geometry parameter is from the well-known parameters by Kasagi & Matsunaga [18]. The engineering drawing of BFS is shown by Table 4 and Figure 1 respectively.

Table 4. BFS geometry

Backward-facing step Geometry			
Step Height (*h*) (mm)	**Upstream height (*H*) (mm)**	**Expansion ratio**	**Total Length (*L*) mm**
41	81	1,5	3050
***Width* (mm)**	20*h*		
Materials and working fluid			
Material	:	Clear acrylic	
Working Fluid	:	Asap (*smoke*)	

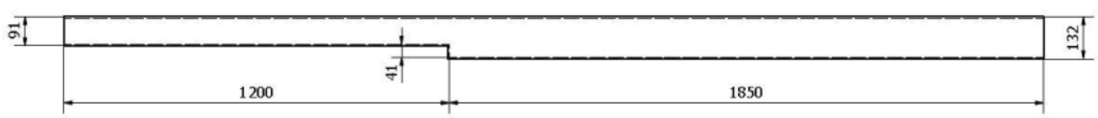

Figure 1. Engineering drawing of BFS (mm)

B. Experimental setup

Experiment conducted according to Figure 2 while the manufactured BFS and experiment condition are shown by Figure 3. Experimental conditionFigure 3**Error! Reference source not found.**. The BFS is manufactured from clear acrylic. The inlet smoke velocity is measured by air flow meter and is a fixed value. Temperature is measured with type-K thermocouple in 5 point along the geometry from upstream to downstream. Temperature data is acquired by National Instrument devices. The smoke entering the BFS through inlet area and exiting the BFS through the outlet area. The smoke is generated by a smoke generator which evaporating the liquid smoke. The double fan which installed at the outlet area then created the suction effect which forced the smoke to the outlet. Suction effect is expected to reduce the pressure drop at inlet area.

The flow process is captured by a low-cost High Definition (HD) video and a LED light at the side view of the geometry and particularly focused in the expansion area so the separation and swirling flow can be captured clearly as well as the reattachment zone. The 5 point temperature measurement are T_1, T_2, T_3, T_4 and T_5 at 50 cm, 155 cm, 260 cm, 310 cm and 360 cm from the inlet, respectively. These 5 point represent 5 location of the BFS;

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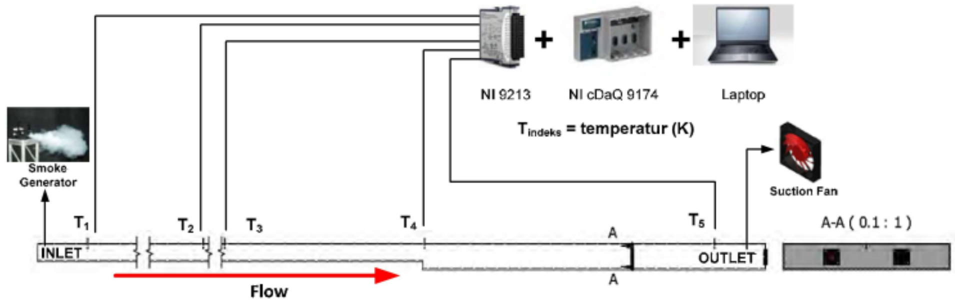
inlet, upstream, downstream, and outlet side. The T_3 and T_4 covered the expansion area, which are 50 cm apart.



T_1 : Fluid temperature at upstream side (°C)
T_2 : Fluid temperature at upstream side (°C)
T_3 : Fluid temperature at upstream side, entering the expansion zone (°C)
T_4 : Fluid temperature at downstream side, exiting the expansion zone (°C)
T_5 : Fluid temperature, toward exit (°C)

Figure 2. Experimental set-up

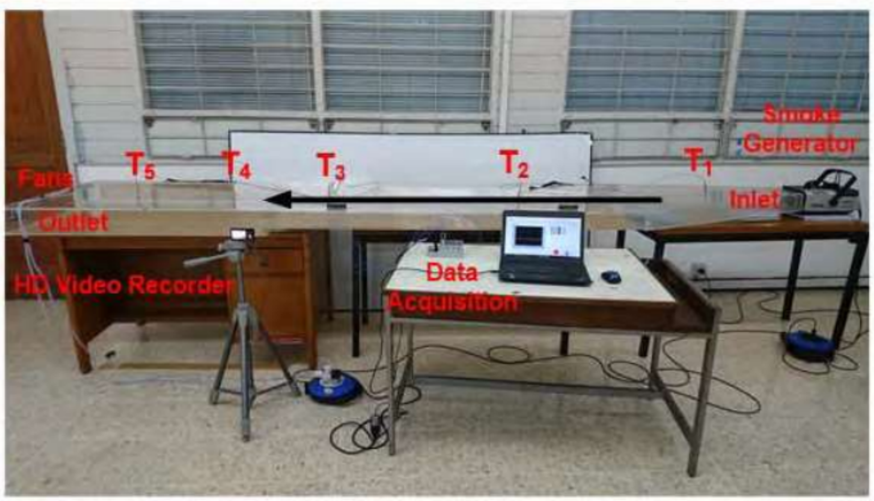


Figure 3. Experimental condition

Reynolds number of the fluid calculated from the measured inlet velocity with flowmeter according to equation (1), which undoubtedly a turbulent flow.

$$Re = \frac{\rho \vec{V} D}{\mu} \tag{1}$$

Ambient temperature = 24,1°C
With :

$\rho_{(24,1^oC)} = 1,876\ kg/m^3$
$\mu_{(24,1^oC)} = 1,844\ N.s/m^2$
$D = inlet\ diameter = 75mm$
$\vec{V} = smoke\ inlet\ velocity = 1,88\ m/s$

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$Re = 14.631$

3. RESULTS AND DISCUSSION

A. Experiment

The separated and swirling flows is captured with HD video camera, 30 frames per second, located at the side-view of the expansion zone. This result is shown on Figure 4 which described the formation process of the swirling flows and how they dissipated. This process took about 15 seconds. Figure 4 consist of 8 flow phase, from unformed swirling flow until dissipated flow. With smoke as the working fluid, number 1 and number 2 show that the swirling flow is unformed and started to form. Number 3 to number 5 show the swirling flow is formed, while number 6 to number 8 show that the swirling flow is dissipated and reattached in the reattachment area. **Error! Reference source not found.** show the temperature acquired along the BFS. T_1 which located nearest the inlet area as the highest temperature. This is because the smoke temperature evaporated from the smoke generator at about 50°C. Other acquired temperature point, the fluid temperature is more stable. T_2 show the upstream temperature, T_3 is upstream temperature, moment before reach the expansion zone and the downstream area, T_4 show the downstream temperature right after the expansion zone and T_5 show the exiting temperature. During the experiment, T_5 experienced the least difference.

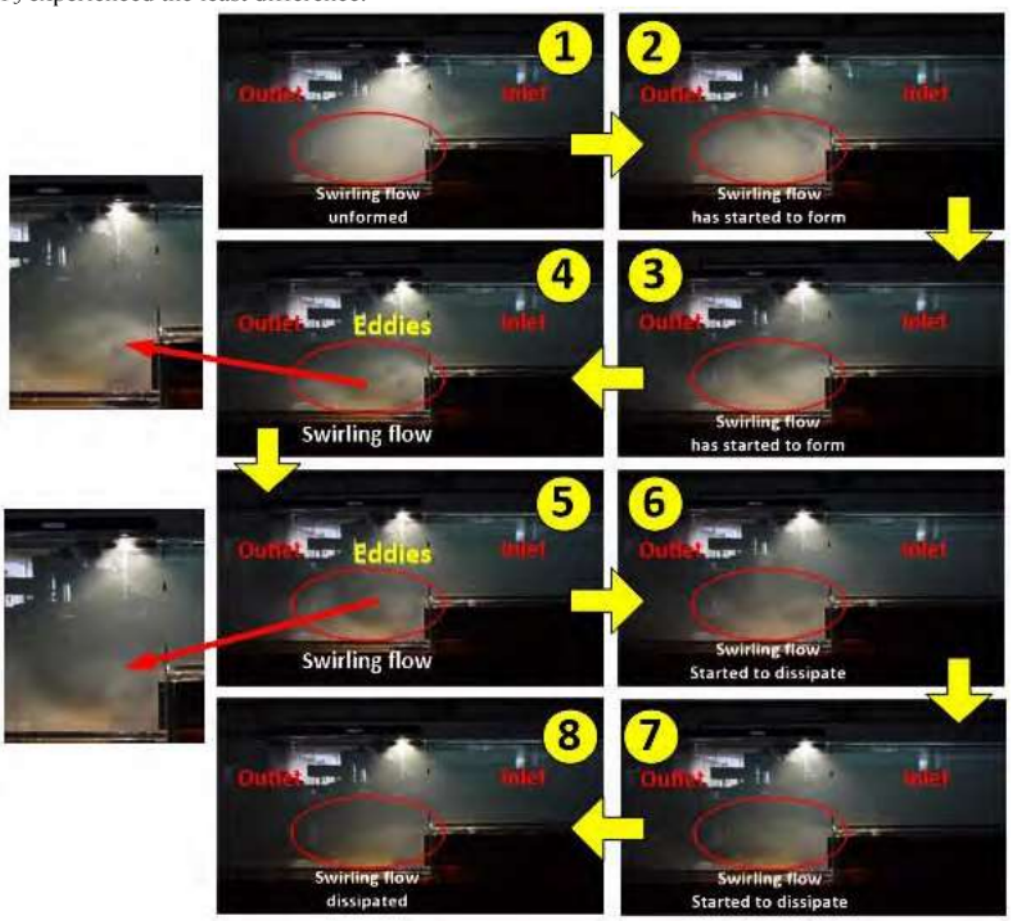

Figure 4. Captured flow at expansion zone

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The fluid temperature along BFS where swirling flows occurred for 15 seconds is shown on Figure 5. The temperature difference of all measured point mainly due to convective heat transfer along the expansion zone. The smoke temperature decreasing to 24°C from 32°C. Largest temperature drop occurs on T_4, the downstream temperature after the flow is expanded. On the 15 seconds of the flow process T_4 14.26% decreased, while the T_3 4.67%. This condition shows that the swirling flow affect the fluid temperature. Direct measurement on the geometry resulting that this swirling and separated flow is occurs on the location around x = 42 mm (x/h = 1.02) from the expansion zone. Swirling flows intensity then decreasing towards the outlet area. Figure 6 which show the temperature of the BFS on non-dimensional x/h clarify the findings from Figure 5. Further research may will need more temperature measurement point, but the swirling flows located between the upstream and downstream area. Point EZ on Figure 6 represent the expansion point, where x is treated to be zero. It is also clear that after reaching the downstream area, the fluid temperature barely declined.

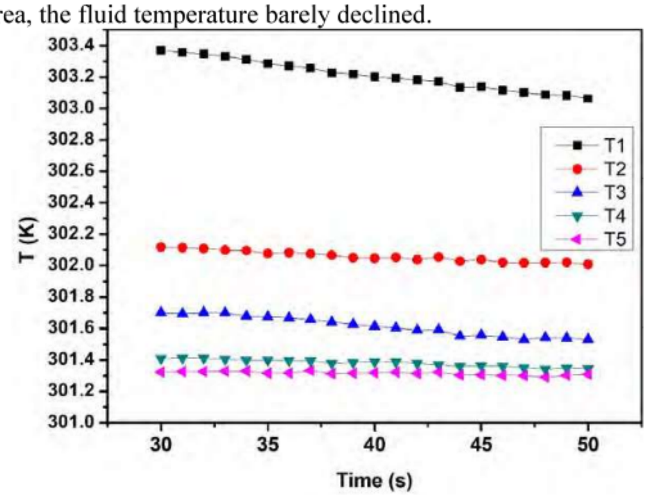

Figure 5. Temperature along expansion zone

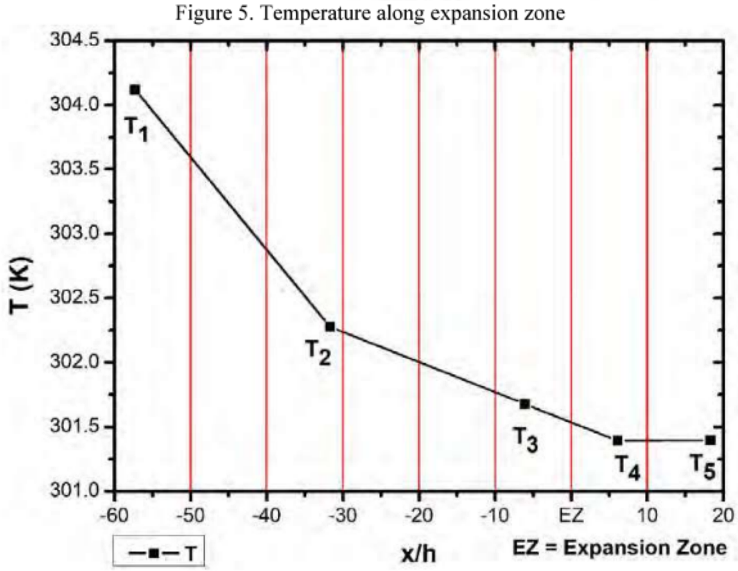

Figure 6. BFS temperature – x/h

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It is already known that swirling flow involving the effect of viscosity and heat diffused. Unlike [14] which analyzed the heat transfer behavior of the separated and swirling flow by Nusselt number (Nu) which represent the ratio of convection and conduction, this paper uses the Prandtl number (Pr) to describe such flow. This is done to accentuate the effect of viscosity to the heat diffused.

$$Pr = \frac{\upsilon}{\chi} \text{ [19]} \qquad (2)$$

With

υ : kinematic viscosity (kg/s.m)

χ : thermal diffusivity (m^2/s)

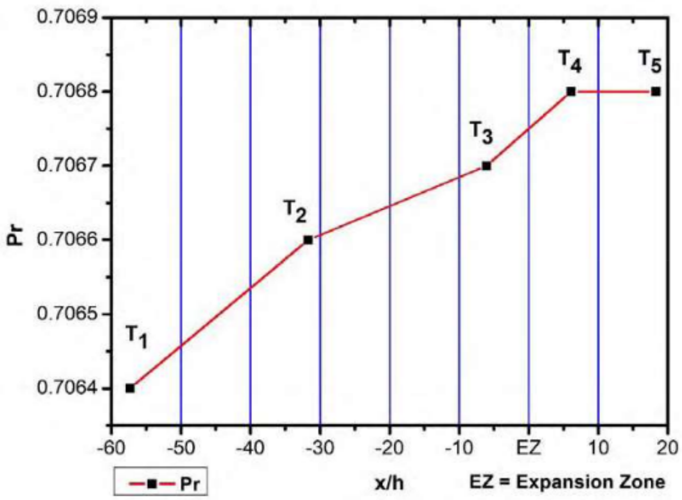

Figure 7. Prandtl number along the BFS

The detailed condition of the flow at expansion area then shown by Prandtl number on Figure 7. It is clear that where the fluid entering the expansion zone, the fluid started to separate and lead to swirl. This condition highly affect the molecular and convective aspect. The experiment revealed that when the temperature is decreasing, heat diffusion is less dominant than the viscosity and yield the increasing of Prandtl number to 0,7068. This increasing Prandtl number also reported by Kanna & Das which indicated that conjugate heat transfer may occur [14]. This result also confirmed by Yakhot et.al, whose reveal that at large Re and not to small Prandtl number, the molecular transport has only very small effect [20]. Nevertheless, more measurement point is needed to describing more precise location of expansion and reattachment point.

4. CONCLUSIONS

Separated and swirling flow of the BFS conducted experimentally with h = 41mm, inlet Re = 14.631 This turbulent flows captured with 30 fps HD video camera, occurs at the expansion zone and reattach at x/h = 1,02. During this swirling process, many phenomenon revealed; this flow is affect the heat dissipated which indicated by the decreasing of temperature. The increasing Prandtl number - which is used as benchmark value - to 0,7068 confirmed that separated and swirling flow lead to domination of convective transport on molecular transport. Although swirling flows is captured in this low-cost research, more improvement need to be done to resulting precise results, including more location of temperature measurement.

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REFERENCES

[1] K. Sarker, M. Ali and Q. Islam, "A numerical study on the physics of flow over a flat plate with backward facing step," *Procedia Engineering,* vol. 90, pp. 351-357, 2014.

[2] T. Lee and D. Mateescu, "Experimental and numerical investigation of 2-D backward-facing step flow," *Journal of Fluids and Structures,* vol. 12, pp. 703-716, 1998.

[3] N. Gautier and J.-L. Aider, "Upstream open loop control of the recirculation area downstream of a backward-facing step," *C.R. Mecanique,* vol. 34, pp. 382-388, 2014.

[4] Y. Rouizi, Y. Favennec, J. Ventura and D. Petit, "Numerical model reduction of 2D steady incompressible laminar flows: Application on the flow over a backward-facing step," *Journal of Computational Physics,* vol. 228, pp. 2239-2255, 2009.

[5] N. Gautier and J.-L. Aider, "Control of the separated flow downstream of a backward-facing step using visual feedback," *Proceedings of The Royal Society A,* vol. 469, no. 2160, 2013.

[6] N. A. C. Sidik, J. Ghaderian and S. Sadeghipour, "Simulation of Turbulent Flow Over a Backward Facing Step Using Lattice Boltzmann Method," *Journal of Engineering Science and Technology,* vol. 86, no. 6, pp. 670-682, 2013.

[7] K. Sarker and H. M. Cho, "Computational Analysis of the Physics of Flow over Backward/Forward Facing Step," *International Journal of Applied Engineering Research,* vol. 11, no. 8, pp. 5549-5554, 2016.

[8] S. Thangam and C. Speziale, "Turbulent Flow Past a Backward-Facing Step: A Critical Evaluation of Two-Equation Models," *AIAA Journal,* vol. 30, no. 5, 1992.

[9] M. A. Kopera, "Direct Numerical Simulation of Turbulent Flow over a Backward-Facing Step," Doctoral Thesis - University of Warwick, 2011.

[10] Anwar-ul-Haque, F. Ahmad, S. Yamada and S. R. Chaudury, "Assessment of turbulence models for turbulent flow over backward-facing step," in *World Congress on Engineering*, London, 2007.

[11] M. A. Hossain, M. T. Rahman and S. Ridwan, "Numerical Investigation of Fluid Flow Thriugh 2-D Backward Facing Step Channel," *International Journal of Engineering Research & Technology,* vol. 2, no. 10, pp. 3700-3708, 2013.

[12] B. Sainte-Rose, N. Bertier, S. Deck and F. Dupoirieux, "A DES method applied to a Backward Facing Step reactive flow," *C. R. Mecanique,* vol. 337, pp. 340-351, 2009.

[13] M. Ramsak, "Conjugate heat transfer of backward-facing step flow: A benchmark problem revisited," *International Journal of Heat and Mass Transfer,* vol. 84, pp. 791-799, 2015.

[14] P. R. Kanna and M. K. Das, "Conjugate heat transfer study of backward-facing step flow - A benchmark problem," *International Journal of Heat and Mass Transfer,* vol. 49, pp. 3929-3941, 2006.

[15] H. Tennekes and J. Lumley, A First Course In Turbulence, 3 rd ed., MIT Press, 1974.

[16] S. Darmawan, A. I. Siswantara, Budiarso, A. Daryus, A. T. Gunawan, A. B. Wijayanto and H. Tanujaya, "Turbulent Flow Analysis in Auxiliary Cross-Flow Runner of a Proto X-3 Bioenergy Micro Gas Turbine Using RNG k-ε Turbulence Model," *ARPN Journal of Engineering and Applied Sciences,* vol. 10, no. 16, pp. 7086-7091, 2015.

[17] S. Darmawan, "Backward-facing step for flow analysis: a review on non-dimensional parameters," *Academic Faculty Development Journals,* p. Will be published, 2016.

[18] N. Kasagi and A. Matsunaga, "Three-dimensional PTV measurement of turbulence

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statistics and energy budget in a backward-facing step flow," *International Journal of Heat and Fluid Flow*, vol. 16, pp. 477-485, 1995.

[19] T. L. Bergman, A. S. Lavine, F. P. Incropera and D. P. Dewitt, Fundamentals of Heat and Mass Transfer, 7th ed., John Wiley & Sons, Inc., 2011.

[20] V. Yakhot, S. A. Orszag and A. Yakhot, "Heat Transfer in Turbulent Fluids - I. Pipe Flow," *Int. J. Heat Mass Transfer,* vol. 30, no. 1, pp. 15 - 22, 1987.

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