Papers of Ship Research Institute, Supplement No.15 (September 1993)

COMPARATIVE CALCULATIONS OF PROPELLERS BY SURFACE PANEL METHOD ——WORKSHOP ORGANIZED BY 20th ITTC PROPULSOR COMMITTEE——

by

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ABSTRACT

Comparative calculations of marine propellers by surface panel method are presented. The plan was organized by 20th ITTC Propulsor committee. Calculation results from 15 organizations are included in the comparison. Results are shown for thrust, torque and pressure distribution on blades. The results of the comparative calculation show the state of the art of surface panel method for marine propellers. The numerical results are useful as the database for marine propellers.

CONTENTS

1 Introduction
2 Surface Panel Method
3 Workshop
4 Sample Propellers and Calculation Conditions
5 Comparative Calculation
6 Calculation Results
6.1 Thrust and Torque
6.2 Pressure Distribution
7 Discussions
8 Conclusion

Acknowledgement

References

Figures

APPENDIX A Calculation Document
APPENDIX B Calculations by DTMB
APPENDIX C Calculations by MIT
APPENDIX D Calculations by AMI
APPENDIX E Calculations by YNU
APPENDIX F Calculations by CETENA

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1 INTRODUCTION

It goes without saying that analysis method for hydrodynamic characteristics of propellers is very important for the development of technology of marine propellers. Today lifting surface theory plays an important role in analysis or design of marine propellers. Recently the application of panel methods to the hydrodynamic analysis of marine propellers becomes active.

20th ITTC Propulsor Committee carried out comparative calculations of marine propeller performance by the surface panel method and a workshop for the discussion of the comparison as Task2 of the committee in order to make clear the accuracy of the panel method for the analysis of marine propellers and to review the applicability of the method. The author was in charge of the task. The intent of the task was to evaluate and promote the use of surface panel methods. This can be accomplished through the comparison of extensive numerical results by many panel methods. The purpose of the comparison is not as a competition but rather as a method to assess the various numerical issues that may be important.

Results of the comparative calculations and workshop are presented in 20th ITTC Report of the propulsor committee [1]. However only the summary of the workshop activities is shown in the report, although many useful data were collected in the project. Many valuable papers were also presented in the workshop. The author wanted to make the extensive valuable data and papers by the contributors open to the public. Almost all results of the comparative calculations are presented in this report. Some papers by the contributors in the workshop are inserted in the appendices of this report by permission of the contributors. They show the state of the art of the surface panel method for marine propellers

2 SURFACE PANEL METHOD

Surface panel method analyzes numerically the potential flow around the lifting body as exactly as possible. The geometry of the lifting body can be treated as accurately as wanted with a very fine panel arrangement on the surface of the lifting body.

We consider a propeller (with duct, stator etc. in case of need) operating in an unbounded flow field. It is assumed that the vortex wake emanating from the trailing edge of the blades is infinitesimally thin and that the flow field except vortex wake is incompressible, inviscid and irrotational. Then there exists a velocity potential in the flow field.

The velocity potential in the flow field is expressed using Green's identity formula and boundary values as

$$\phi = -\frac{1}{4\pi}\iint \frac{\partial \phi}{\partial n'}\frac{1}{r}\,dS + \frac{1}{4\pi}\iint \phi \frac{\partial}{\partial n'}\left(\frac{1}{r}\right) dS \tag{1}$$

Equation (1) is the basic starting formula for panel methods [2]. The velocity is expressed as

$$V = \nabla\phi = -\frac{1}{4\pi}\iint \frac{\partial \phi}{\partial n'}\nabla\frac{1}{r}\,dS + \frac{1}{4\pi}\iint \phi \nabla \frac{\partial}{\partial n'}\left(\frac{1}{r}\right) dS \tag{2}$$

The velocity field produced by the doublet distribution on panels is given by the second term of equation (2). This term can be integrated by parts to obtain

$$V_D = \nabla\phi_D = \frac{1}{4\pi}\iint \gamma \times \nabla\left(\frac{1}{r}\right) dS - \frac{1}{4\pi}\int \phi \nabla\left(\frac{1}{r}\right) \times t\,ds \tag{3}$$

The surface panel method employs one of the above equations(1) through (3). Singularities such as source, doublet (potential itself), or vorticity are distributed on the body surface which is a boundary of the flow field. The problem is solved using an integral equation with a boundary condition. The equation is discretised for numerical calculation. The variety of surface panel methods is due to the choice of the integral equations, singularities, and the method of discretisation. For instance potential based panel method employs Eq.(1). Surface vortex lattice method employs Eq.(3).

3 WORKSHOP

20th ITTC Propulsor Committee distributed a questionnaire outlining the plan of the comparative calculation and called for contributions to 98 organizations on June 24,1991. 16 organizations signified their intention to perform the comparative calculation.

The committee furnished them with the calculation documents (Appendix A) on Feb.4,1992. 15 organizations sent the committee the results of their calculations. The workshop was held in Seoul, Korea on August 23, 1992.

In the workshop 19 participants attended, 10 participants presented the results of their calculations and the use of the surface panel method for marine propellers was discussed. Organizations of the participants are listed in Table 1. Papers contributed by the participants to the comparative calculation are listed in Tables 2(a),2(b). Some of them are printed in Appendices of this report (Appendix B, C, D, E, F).

Table 1 List of Organizations Contributing to Workshop on Surface Panel Method for Marine Propellers

Massachusetts Institute of Technology, USA
Analytical Methods,Inc., USA
Chungnam National University, Korea
Korean Research Institute of Ships and Ocean Engineering, Korea
Hyundai Heavy Industries, Korea
Samsung Heavy Industries, Korea
Mitsubishi Heavy Industries,Ltd. Nagasaki R&D Center, Japan
Nippon Kaiji Kyokai, Research Institute, Japan
Yokohama National University, Japan
Ship Research Institute, Japan
Cento per gli Studi di Tecnica Navale CETENA, Italy
Bassin d'Essais des Carenes, France
Maritime Research Institute Netherlands, The Netherlands
Delft University of Technology, The Netherlands
Versuchsanstalt fur Wasserbau & Schiffbau, Germany
Canal Experiencias Hidrodinamicas, Spain

Table 2(a) Distributed Materials for the workshop

1) K.Koyama: Comparative Calculation of Propellers by Surface Panel Method from All Participants
2) Cheng-I Yang: Prediction of Hydrodynamic Performance of DTMB Propellers 4119 and 4842 with a Panel Method
3) Ching-Yeh Hsin and Justin E.Kerwin: Steady Performance Analysis for Two Propellers using MIT-PSF-10
4) B.Maskew, J.S.Fraser, J.B.Murray and J.M.Summa: Calculations for the DTRC 4119 and DTRC 4842 Propellers Using VSAERO/MPROP and USAERO Panel Codes
5) J.-T.Lee,Y.-G.Kim,J.-C.Suh, and C.-S.Lee: Calculation of the Propeller Performance by a Surface Panel Method
6) T.Hoshino: Results of Comparative Calculation of Propellers by Surface Panel Method
7) S.Ryo: Calculation results of DTRC4119 and DTRC4842 by NK's computer code based on Boundary Element Method (Panel Method)
8) S.Ryo,Y.Sasaki and late M.Takahashi: Analysis of Three Dimensional Flow around Marine Propeller by Direct Formulation of Boundary Element Method,ISPC92,China
9) H.Yamasaki: Calculation by Surface Vortex Lattice Method
10) K.Koyama: Calculation of Propellers DTRC4119 and DTRC4842 by Surface Panel Method
11) G.Caprino, L.Sebastiani, M.Caponnetto, and M.De Benedetti: Propanel: A Surface Panel Method for the Steady Analysis of Naval Propellers
12) R.Baubeau: Comparative Calculation of Propellers by Surface Panel Method
13) P.Sander: Calculation of the pressure distribution on a propeller blade with a continue Method
14) H.Streckwall: Calculations for the 20th ITTC Propulsor Committee

Table 2(b) Supplementary Materials for the workshop

1) 20th ITTC Propulsor Committe, Comparative Calculation of Propellers by Surface Panel Method; Calculation Document, February 4,1992
2) J.-C.Suh: Analytical Evaluation of the Surface Integral in the Singularity Methods, Transactions of SNAK, Vol.29, No.1, March 1992
3) T.Hoshino: A Surface Panel Method with a Deformed Wake Model to Analyze Hydrodynamic Characteristics of Propellers in Steady Flow, Mitsubishi Technical Bulletin MTB195 April 1991
4) K.Koyama: Application of a Panel Method to the Unsteady Hydrodynamic Analysis of Marine Propellers, 19th ONR, Aug.1992
5) N.Kroll, D.Lohmann, and J.Schone: Numerical Methods for Propeller Aerodynamics and Acoustics at DFVLR, AGARD Paper69-24,May 1987
6) F.Genoux, R.Baubeau, A.Bruere, and M.DuPont: Steady and Unsteady Characteristics of a Propeller Operating in a Non-Uniform Wake: Comparisons Between Theory and Experiments, 18th ONR, 1990
7) K.Yossifov,BSHC: Propeller Comparative Calculations with Application of the Surface Panel Method
8) A.Haimov,D.Minchev, and T.Videv: Off-Design Propeller Performance Prediction Based on a Deformed Slipstream Model, 5th Int. Congress on Marine Tech., Athens,1990
9) Dang Jie and Tang Denghai : ITTC Comparative Calculation of Propellers
10) S.D.Jessup : An Experimental Investigation of Viscous Aspects of Propeller Blade Flow, The Catholic Univ. of America,1989

4 SAMPLE PROPELLERS AND CALCULATION CONDITIONS

Experimental data are very important for the evaluation of the surface panel method. S.D.Jessup presented detailed measurement for flow around propellers in his dissertation [3]. One of his propellers DTRC4119 is used in the comparative experiments on viscous effects for Task 1 of the 20th ITTC Propulsor Committee.

Two propellers DTRC4119 and DTRC4842 were selected as the propellers for the comparative calculation. DTRC4119 is a three bladed propeller with neither rake nor skew. DTRC4842 is a five bladed propeller with high skew. Their geometries are shown in Table 3(a),(b),(c). Detail of their geometry is presented in the calculation document (Appendix A). Photographs of the propellers are shown in Fig.1.1.1 of Appendix A.

At the workshop the comparative calculations were discussed for the fictitious propeller DTRC4842I instead of DTRC4842 because of confusion over the rake distribution of DTRC4842. Propeller DTRC4842I, which is shown as DTRC4842 in the calculation document, has different rake distribution i_T/D from DTRC4842. Rake distribution i_T/D of DTRC4842 is shown in Table 3(b), whereas that of DTRC4842I is shown in Table 1.1.2(a) of Appendix A. After the workshop many participants reperformed the calculation for DTRC4842. The results for DTRC4842 and DTRC4842I are presented in this report.

Table 3(a) Geometry of DTRC 4119

Diameter, D: 1.00 ft. (0.305 m)
Rotation: Right Hand
Number of Blades: 3
Hub-Diameter Ratio: 0.20
Skew, θ_s,Rake,i_T: none
Design Advance Coefficient, J: 0.833
Section Thickness Form: NACA66(DTRC Modified)
Section Meanline: NACA, a=0.8
Design Thrust Coefficient, K_T: 0.150

r/R	C/D	P/D	θ_s (degree)	i_T/D	t_M/C	f_M/C
0.2	0.320	1.105	0	0	0.2055	0.01429
0.3	0.3635	1.102	0	0	0.1553	0.02318
0.4	0.4048	1.098	0	0	0.1180	0.02303
0.5	0.4392	1.093	0	0	0.09016	0.02182
0.6	0.4610	1.088	0	0	0.06960	0.02072
0.7	0.4622	1.084	0	0	0.05418	0.02003
0.8	0.4347	1.081	0	0	0.04206	0.01967
0.9	0.3613	1.079	0	0	0.03321	0.01817
0.95	0.2775	1.077	0	0	0.03228	0.01631
1.0	0.0	1.075	0	0	0.03160	0.01175

Table 3(b) Geometry of DTRC 4842

Diameter, D: 1.219 ft. (0.3717 m)
Rotation: Right Hand
Number of Blades: 5
Hub-Diameter Ratio: 0.323
Design Advance Coefficient, J: 0.905
Section Thickness Form: NACA66(DTRC Modified)
Section Meanline: Specified
Design Thrust Coefficient, K_T: 0.306

r/R	C/D	P/D	θ_s (deg.)	i_T/D	t_M/C	f_M/C
0.323	0.2015	0.9321	0.38	0.0010	0.2179	0.0100
0.35	0.2181	1.0790	-3.07	-0.0090	0.1871	0.0158
0.4	0.2494	1.2361	-6.82	-0.0229	0.1415	0.0253
0.5	0.3113	1.4194	-9.02	-0.0369	0.0854	0.0365
0.6	0.3664	1.4892	-7.57	-0.0325	0.0581	0.0390
0.7	0.4031	1.488	-3.24	-0.0136	0.0444	0.0371
0.8	0.4090	1.329	4.34	0.0165	0.0379	0.0319
0.9	0.3651	1.0759	13.75	0.0423	0.0356	0.0264
0.95	0.3106	0.9012	19.25	0.0509	0.0363	0.0247
1.0	0.0700	0.6981	25.42	0.0561	0.0880	0.0243

Table 3(c) Thickness and Camber Distributions for DTRC 4119 and 4842

X_c	t/C	f/C,4119	f/C,4842
0.0000	0.0000	0.0000	0.0000
0.0125	0.2088	0.0907	0.0875
0.0250	0.2932	0.1586	0.1530
0.0500	0.4132	0.2712	0.2625
0.0750	0.5050	0.3657	0.3585
0.1000	0.5814	0.4482	0.4415
0.1500	0.7042	0.5869	0.5803
0.2000	0.8000	0.6993	0.6955
0.3000	0.9274	0.8635	0.8630
0.4000	0.9904	0.9615	0.9630
0.4500	1.0000	0.9881	0.9907
0.5000	0.9924	1.0000	1.0000
0.6000	0.9306	0.9786	0.9750
0.7000	0.8070	0.8892	0.8777
0.8000	0.6220	0.7027	0.6760
0.9000	0.3754	0.3586	0.3613
0.9500	0.2286	0.1713	0.1785
1.0000	0.0666	0.0000	0.0000

Table 4 Standard Calculation Cases

A) DTRC4119	J=0.833	recomended paneling	
	without hub	linear wake	
B) DTRC4119	J=0.833	reference paneling	
	without hub	linear wake	
C) DTRC4119	J=0.833	recomended paneling	
	with hub	linear wake	
D) DTRC4119	J=0.833	recomended paneling	
	without hub	devised wake	
E) DTRC4119	J=0.833	recomended paneling	
	with hub	devised wake	
F) DTRC4119	J=1.100	recomended paneling	
	without hub	linear wake	
G) DTRC4119	J=1.100	recomended paneling	
	without hub	devised wake	
H) DTRC4842	J=0.905	recomended paneling	
	with hub	devised wake	
I) DTRC4842I	J=0.905	recomended paneling	
	with hub	devised wake	

recommended paneling :
paneling participants recommend or use

reference paneling :
fine or course or lower order or higher order paneling which shows the validation of the paneling participants recommend

linear wake :
blade vortex wake remains its location at the point it has emanated in spite of induced velocity

devised wake :
modeled wake or calculated wake

The advance coefficients J=0.833 and J=1.100 are for DTRC4119, and J=0.905 for DTRC4842 and DTRC4842I. Details of the calculation conditions are shown in Table 4.

5 COMPARATIVE CALCULATION

The list of contributors from the 15 organizations who sent the calculation results is shown in Table 5.

The calculation methods and their characteristics are shown in Table 6. Many researchers use a potential based panel method and employ plane panels or hyperboloidal panels. Many researchers use the pressure Kutta condition. The coarsest paneling in the table is NR×NC = 7×8. The finest paneling is NR×NC = 30 ×20 and 15×30.

Some calculations based on lifting surface theory were contributed to the workshop and were included for reference.

Table 5 List of Participants to Comparative Calculation

1) Dr.Cheng-I. Yang
David Taylor Model Basin (DTMB), USA
2) Prof.J.E.Kerwin,Dr.C.Y.Hsin,Dr.S.Kinnas
Massachusetts Institute of Technology (MIT), USA
3) Dr.B.Maskew
Analytical Methods,Inc. (AMI), USA
4) Dr.J.T.Lee,Mr.Y.G.Kim,Dr.J.C.Suh,Prof.C.S.Lee
Korean Research Institute of Ships and Ocean Engineering (KRISO), and Chungnam National University (CNU), Korea
5) Dr.T.Hoshino
Mitsubishi Heavy Industries,Ltd. Nagasaki R&D Center (MHI), Japan
6) Dr.S.Ryo
Research Institute, Nippon Kaiji Kyokai (NK), Japan
7) Mr.H.Yamasaki
Yokohama National University (YNU), Japan
8) Dr.K.Koyama
Ship Research Institute (SRI), Japan
9) Dr.G.Caprino
Cento per gli Studi di Tecnica Navale (CETENA), Italy
10) Dr.Dieter Lohmann
Deutsche Forschungsanstalt fur Luft und Raumfahrt (DLR), Germany
11) Prof.P.Bogdanov,
Bulgarian Ship Hydrodynamics Centre (BSHC), Bulgaria
12) Dr.R.Baubeau
Bassin d'Essais des Carenes (DGA), France
13) Dr.P.Sander
Institut fur Schiffbau Universitat Hamburg (Hamburg), Germany
14) Dr.H.Streckwall
Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA), Germany
15) Mr.Dang Jie, and Mr.Tang Denghai
China Ship Scientific Research Center (CSSRC), China

6 CALCULATION RESULTS

Standard calculation conditions are case A, case B,,, case I as shown in Table 4. Some

Table 6 (a) Calculation Method

		Calculation Method	Panel Type	NR × NC	Kutta Condition
1)	DTMB	Potential based P.M. (DTMB ver. of VSAERO)	Quadrilateral plane panel	10 × 29	
2)	MIT	Potential based P.M. (MIT-PSF-10)	Hyperboloidal	30 × 20	Iterative Pressure Kutta Condition
3)	AMI	Potential based P.M. (VSAERO, USAERO)		15 × 30	
4)	KRISO/ CNU	Potential based P.M. (KPA11)	Hyperboloidal panel	10 × 20	Pressure Kutta Condition
5)	MHI	Potential based P.M.	Hyperboloidal quadrilateral panel	12 × 12	Pressure Kutta Condition
6)	NK	Direct Formulation of BEM (Potential based P.M.)	Triangular element	8 × 13	Pressure Kutta Condition
7)	YNU	Surface Vortex Lattice M.	Horse-shoe	10 × 12	Nothing
8)	SRI	Potential based P.M. Time-Stepping code	Quadrilateral plane panel	7 × 8	Modified Morino Kutta Condition
9)	CETENA	Potential based P.M.	Quadrilateral plane panel	17 × 12	Trial And Error technique based on linear interpolation
10)	DLR	Lifting Surface Theory based on FW-H equation	plane panel	10 × 15	Geometric Kutta Condition (bisector, 2% of chord)
11)	BSHC	Lifting Surface Theory		15 × 9	
12)	DGA	Lifting Surface Theory Quasi-Continuous Method		12 × 12	
13)	Hamburg	Lifting Surface Theory Continue Method(Mode Function Method)			
14)	HSVA	Lifting Surface Theory Vortex-Lattice Method		10 × 10	
15)	CSSRC	Potential Based P.M. (MBPM-V1.0)	Hyperboloidal quadrilateral panel	10 × 16	Pressure Kutta Condition

NR : number of panels in radial direction
NC : number of panels in chordwise direction

Table 6 (b) Calculation Method

		Cal. of Velocity	Viscous Correction
1)	DTMB		Sectional drag coefficient (empirical correction)
2)	MIT	2nd Oder Finite Difference Scheme	Sectional drag coefficient
3)	AMI		Boundary layer calculation
4)	KRISO/ CNU	Numerical Differentiation Piecewise Quadratic Inter.	Viscous friction coefficient C_F=0.004
5)	MHI		Empirically determined formula for frictional drag
6)	NK	Numerical Differentiation 1st order shape function	drag coefficient
7)	YNU	Numerical cal.by Biot-Savart Low	Prandtl-Schlichting formula for drag
8)	SRI	Numerical Differentiation Quadric curved surface	Exp. data for section drag and circulation reduction Abbot and Von Doenhoff
9)	CETENA	Numerical Differentiation Pot. expressed by parabola	Van Oossanen $Cr = Cf\ (1+1.2t/c+70(t/c)^4)$
10)	DLR		Transpiration method - boundary layer calculation from previous pressure distribution
11)	BSHC		drag coefficient and circulation reduction
12)	DGA		integrating local flat plate friction coefficient
13)	Hamburg		
14)	HSVA	Biot-Savart	Sectional drag coefficient
15)	CSSRC	Numerical Differentiation	Viscous friction coefficient $Cf=0.026Res^{-1/7}$

participants carried out calculations for all cases. Others carried out some parts of the cases. Results of all the calculations were discussed in the workshop.

Examples of paneling for the propellers are seen in Figs.1,8 of Appendix B, Figs.1,2 of Appendix C, or Figs.4.1,4.8 of Appendix D.

6.1 THRUST AND TORQUE

Calculation results for thrust coefficient K_T and torque coefficient K_Q are shown in Fig.1.1.1 - Fig.1.6.2.

The case A (DTRC4119, J=0.833, without hub, linear wake) without viscous correction is the most basic case. The case is suitable for the validation of numerical results. K_T, K_Q values for the case are shown in Fig.1.1.1(a),(c). Correlation between calculation and experiment is reasonable. However the scatter of the calculation results is somewhat unexpected. A possible reason for the scatter may be that some calculations modify the pitch of the vortex wake in spite of linear calculation.

Calculation results for the case A with viscous correction are shown in Fig.1.1.1(b),(d). Improvement of the correlation with experiment is shown.

Calculation results for the case C (DTRC4119, J=0.833, with hub, linear wake) are shown in Fig.1.2.1(a),(b),(c),(d). Comparison between case C and case A shows the effect of hub. The effect is not so large in this case. Detailed survey of the effect is discussed in materials presented by MIT (Appendix C) . In order to understand the effect of the hub geometries, they have calculated the forces on propeller DTRC4119 by using three different hub geometries, along with the no hub results. Besides the hub model suggested by ITTC, they also used hub geometries with constant radii downstream and upstream.This corresponds to the real experiments in which the propellers may be driven either from upstream, or from downstream. Fig.5 of Appendix C shows these three different hub models. Results of their calculation are shown in Fig.6 of Appendix C.

Calculation results for the case D (DTRC4119, J=0.833, without hub, devised wake) are shown in Fig.1.3.1(a),(b),(c),(d). Comparison between case D and case A shows the effect of devised wake.

The case E (DTRC4119, J=0.833, with hub, devised wake) with viscous correction is most realistic case. The case is suitable for comparison with experiment. K_T, K_Q values for the case are shown in Fig.1.4.1(b),(d). Correlation between calculation and experiment is good which demonstrates the value of the surface panel method. The correlation for K_Q is not as good as that for K_T. Although viscous effect, devised wake effect and hub effect are included in case E, the viscous effect is dominant for K_Q.

Calculation results of the case H for DTRC4842 are shown in Fig.1.5.1(b),(d). The correlation between calculation and experiment has the same tendency as the case for DTRC4119.

Calculation results of the case I for DTRC4842I are shown in Fig.1.6.1. The comparison between case I and case H shows the effect of rake.

Calculation results by the lifting surface theory are shown in Fig.1.1.2, 1.2.2, 1.3.2, 1.4.2, 1.6.2.

6.2 PRESSURE DISTRIBUTION

Calculation results for pressure coefficient C_P are shown in Fig.2.1.1 - Fig.2.7.1.

Pressure coefficients C_P for the case A for DTRC4119 are shown in Fig.2.1.1 (a),(b),(c),(d),(e),(f). The small scatter shows the merit of surface panel methods. It becomes clear when we compare these results with 15th ITTC Comparative Calculations of Propeller Blade Pressure Distributions [4]. On the whole the results for C_P on the blade are considered to be satisfactory although there is considerable scatter near the root, tip, leading edge, and trailing edge.

Calculation results for the case C are shown in Fig.2.2.1. The effect of the hub makes pressure low at 0.3R back and face.

Calculation results for the case D are shown in Fig.2.3.1. Discrepancies between the case D and the case A seems not to be large.

Pressure coefficients C_P for the case E are shown in Fig.2.4.1(a),(b),(c),(d),(e),(f). Correlation between calculations and experiment in general, is good although many calculations for $-C_P$ near the root r/R=0.3 is higher than the experiment.

Calculation results for the case F and the case G are shown in Fig.2.5.1.

Pressure coefficients C_P for the case H for DTRC4842 are shown in Fig.2.6.1 (a),(b),(c),(d),(e),(f). There seems to be more scatter in the results.

Calculation results for the case I for

DTRC4842I are shown in Fig.2.7.1. Comparison between the case I and the case H shows the effect of rake.

Calculation results for DTRC4119 by lifting surface theory are shown in Fig.2.1.2.

7 DISCUSSIONS

Detailed comparison between case A through case G reveals the viscous effect, the effect of hub and the effect of devised wake on the thrust, torque, and the pressure distribution.

Viscous effect on K_T,K_Q values is shown in Fig.2 and Fig.9 of Appendix B (DTMB). Viscous drag correction is essential to the correct prediction of the torque. Its effect on the prediction of the thrust is marginal.

The effect of hub appears as a low pressure on the blade near hub. The effect of hub on thrust and torque is small in these calculation cases.

Although the effect of the devised wake does not seem to be completely clear, the devised wake is very different from that of classical propeller theory. Examples of the devised wake are shown in Fig.3 (cited from the materials presented by MHI, No.6 in Table 2(a) of this report). Further study on the deformation of the vortex wake is expected.

8 CONCLUSION

The results of the comparative calculation show the state of the art of surface panel method for marine propellers. The numerical results are useful as the database for marine propellers. Conclusions of the comparative calculations and workshop are as follows,

1. The results of comparative calculations demonstrate the value of panel methods for propeller analysis. Most of the methods are potential based, rather than velocity based.

2. The predictions of performance for propellers are generally in good agreement with the experimental data.

3. Panel methods predict the pressure distribution well except near the root, tip, leading edge and trailing edge. Further investigation on the arrangements of panels close to the root, tip, leading edge and trailing edge is required in order to improve the accuracy of predictions.

4. For further development, the treatment of viscous corrections and the slipstream wake model must be studied.

ACKNOWLEDGEMENT

These comparative calculations and the workshop were accomplished through the considerable effort of all participants. Participants in the comparative calculations are listed in Table 5 and the participants in the workshop are listed in Table 1. Korean colleague, Dr.H.S.Lee contributed in the preparation for the workshop and KTTC supported the workshop with the conference room and many conveniences. The author would like to express his sincere gratitude to all participants, Dr.H.S.Lee and KTTC.

The author also wishes to express his indebtedness to the members of 20th ITTC Propulsor Committee

Dr. Frank B. Peterson, NSWC, USA (Chairman)
Prof. Shi- Tang Dong, CSSRC, China
Dr. A. Gorschkov, KSRI, Russia
Dr. Alfred M. Kracht, VWS, Germany
Dr. Ramon Quereda Lavina, PARDO TANK, Spain
Dr. Giovanni Caprino, CETENA, Italy
Dr. Jaakko Pylkkanen, VTT, Finland
Mr. Colin Wills, DRA, UK

for their support and cooperation.

Furthermore the author is grateful to Mr.K.Awai for drawing the figures.

The author also wishes to express his indebtedness to the editorial committee of Ship Research Institute.

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[2] Koyama,K. et al., "Experimental Investigation of Flow Around a Marine Propeller and Application of Panel Method to the Propeller Theory," 16th Symposium on Naval Hydrodynamics,1986, Berkeley

[3] Jessup,S.D., "An Experimental Investigation of Viscous Aspects of Propeller Blade Flow," The Catholic University of America, PHD Thesis, 1989

[4] 15th ITTC Report of Propeller Committee, Sept. 1978, the Hague, page 266

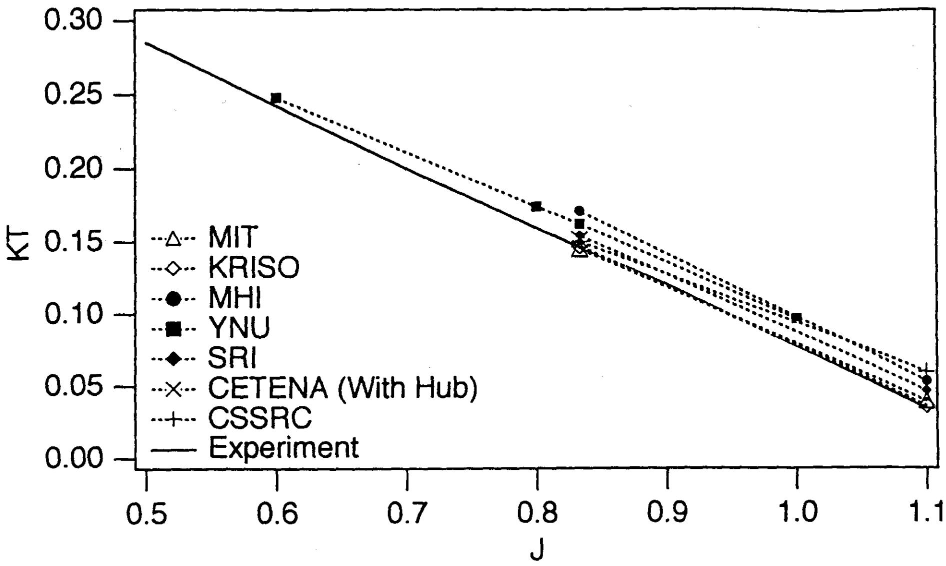

Fig.1.1.1(a) Case A , DTRC4119 , Without Hub , Linear Wake
KT Without Viscous Correction

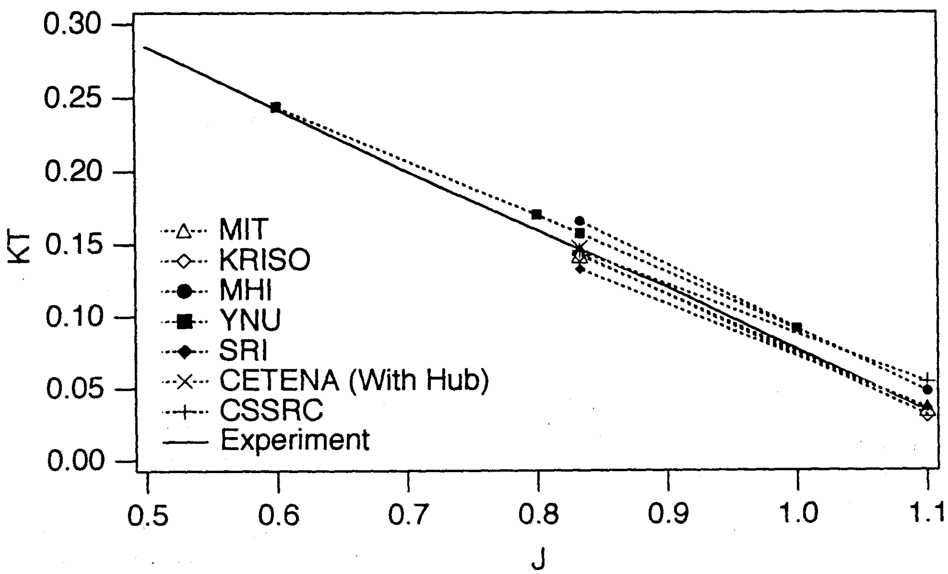

Fig.1.1.1(b) Case A , DTRC4119 , Without Hub , Linear Wake
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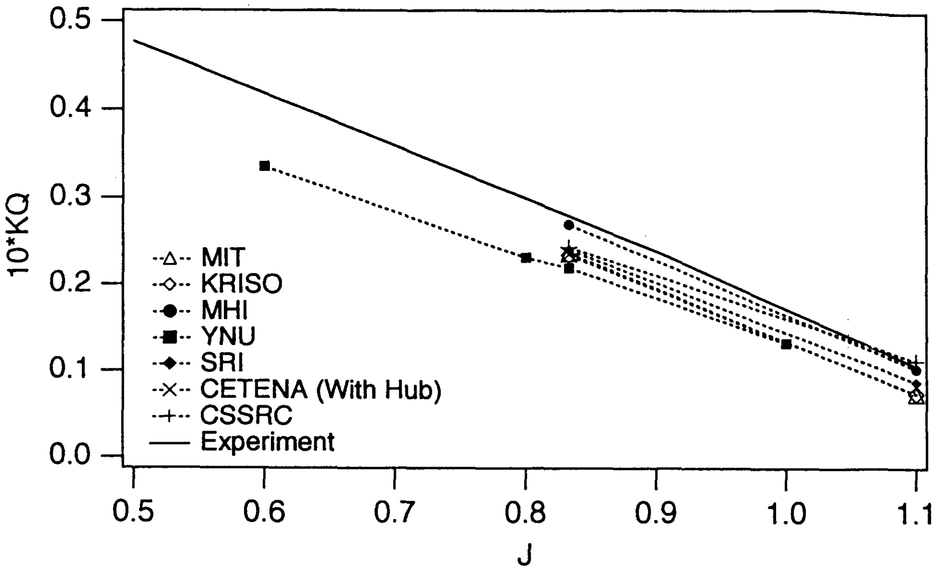
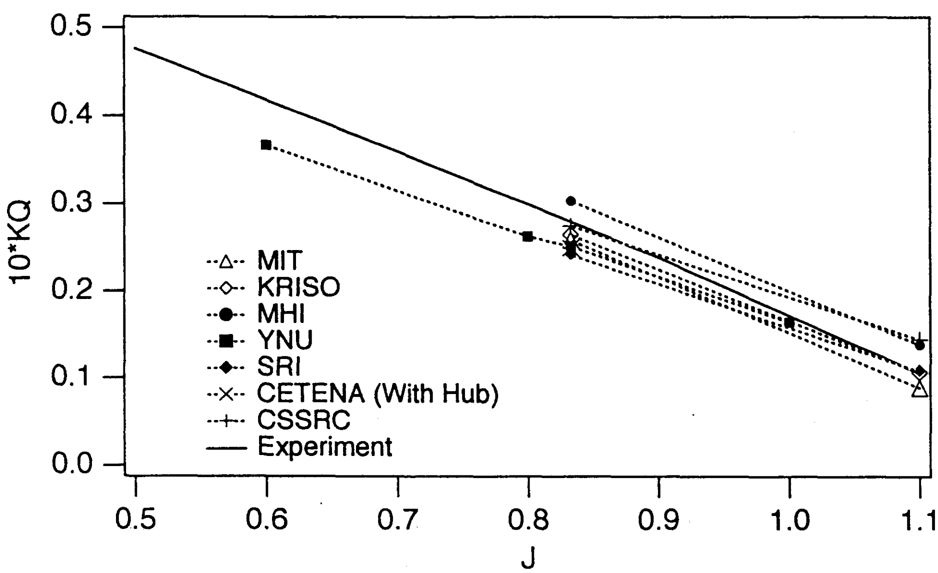


Fig.1.1.1(c) Case A , DTRC4119 , Without Hub , Linear Wake
KQ Without Viscous Correction



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KQ With Viscous Correction

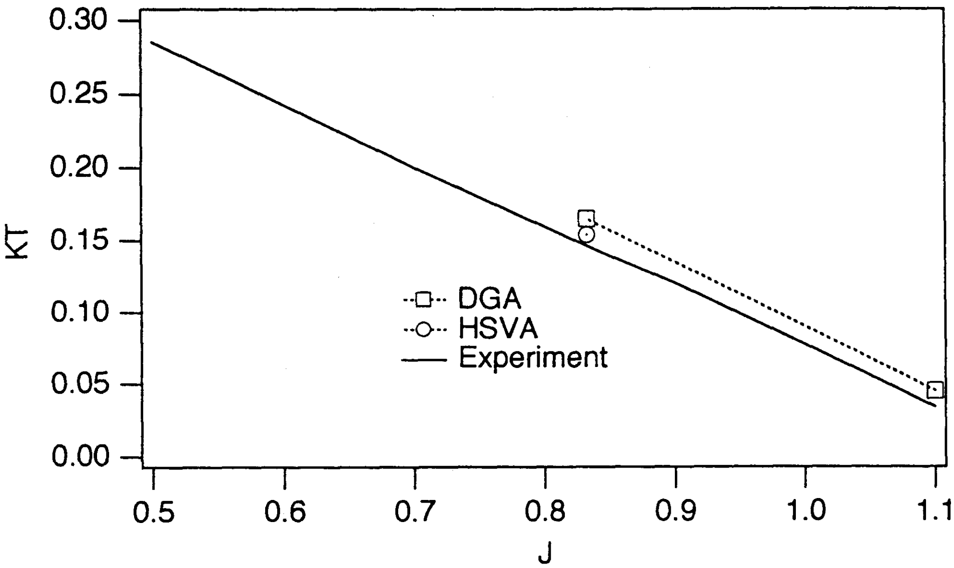

Fig.1.1.2(a) Case A , DTRC4119 , Without Hub , Linear Wake
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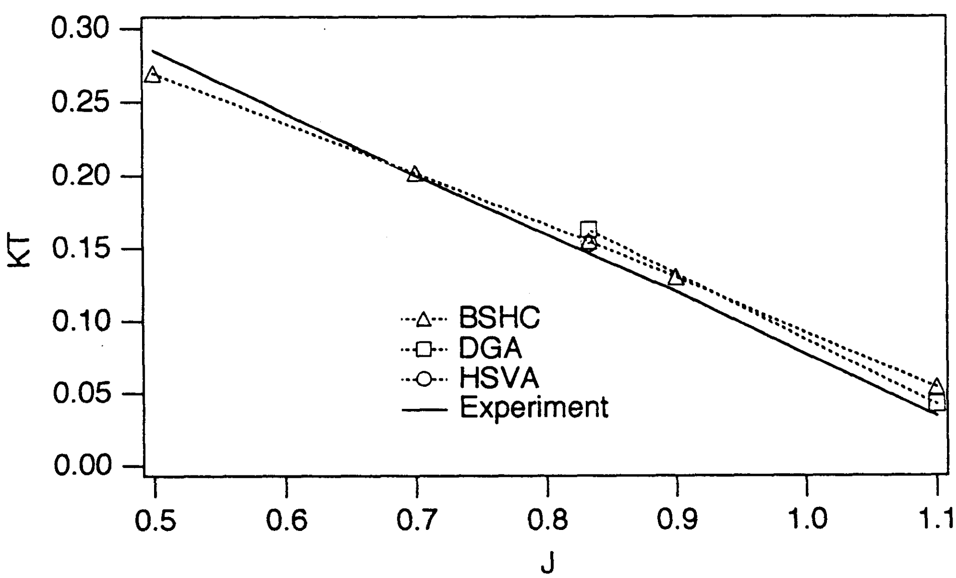

Fig.1.1.2(b) Case A , DTRC4119 , Without Hub , Linear Wake
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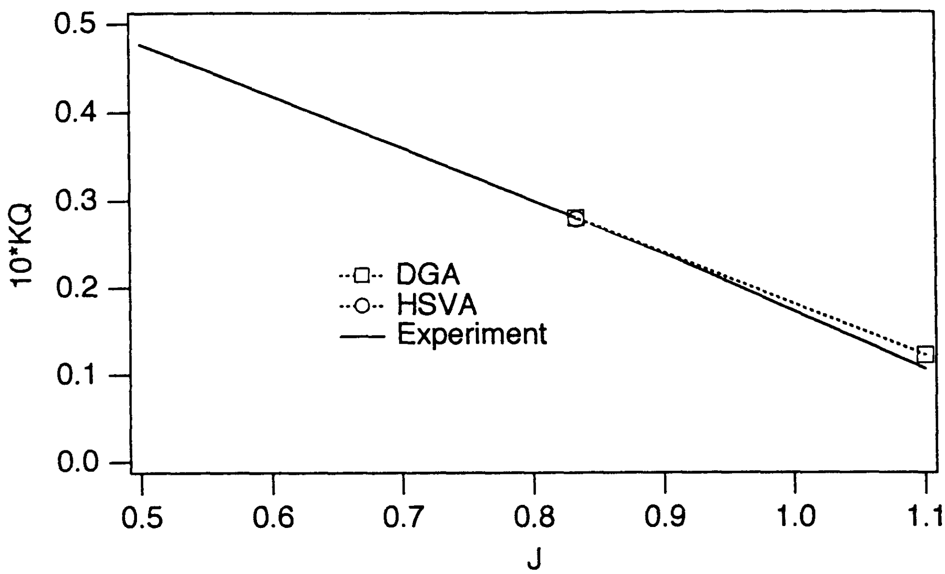

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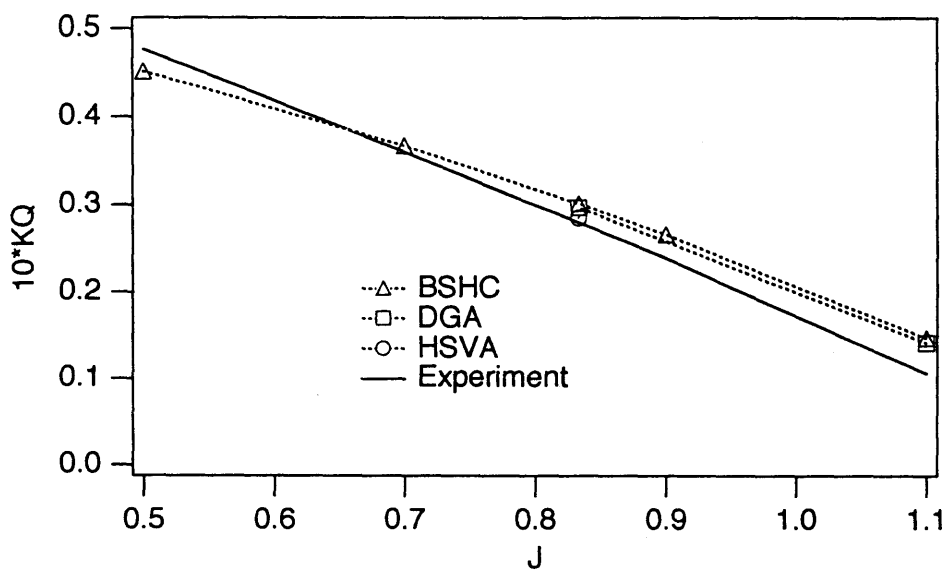
KQ Without Viscous Correction



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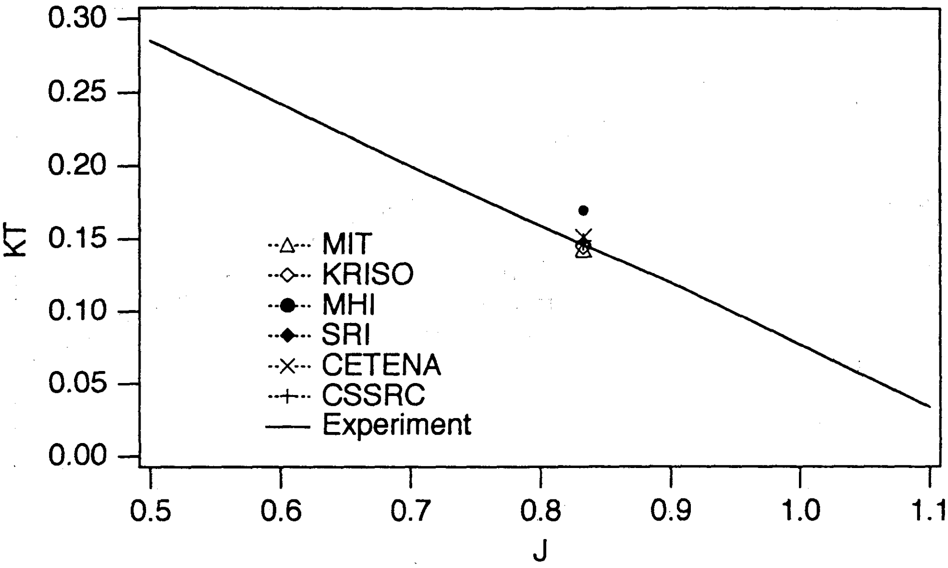

Fig.1.2.1(a) Case C , DTRC4119 , With Hub , Linear Wake
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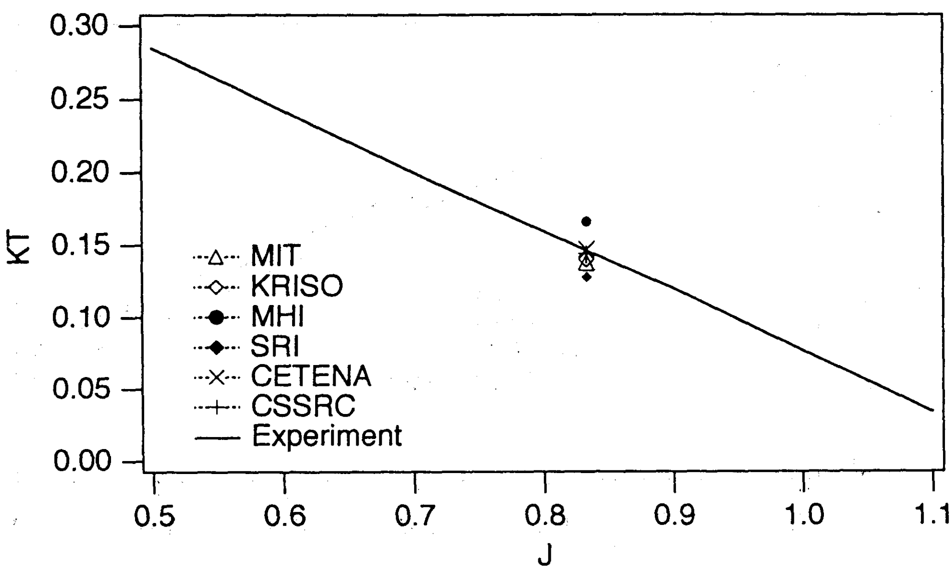

Fig.1.2.1(b) Case C , DTRC4119 , With Hub , Linear Wake
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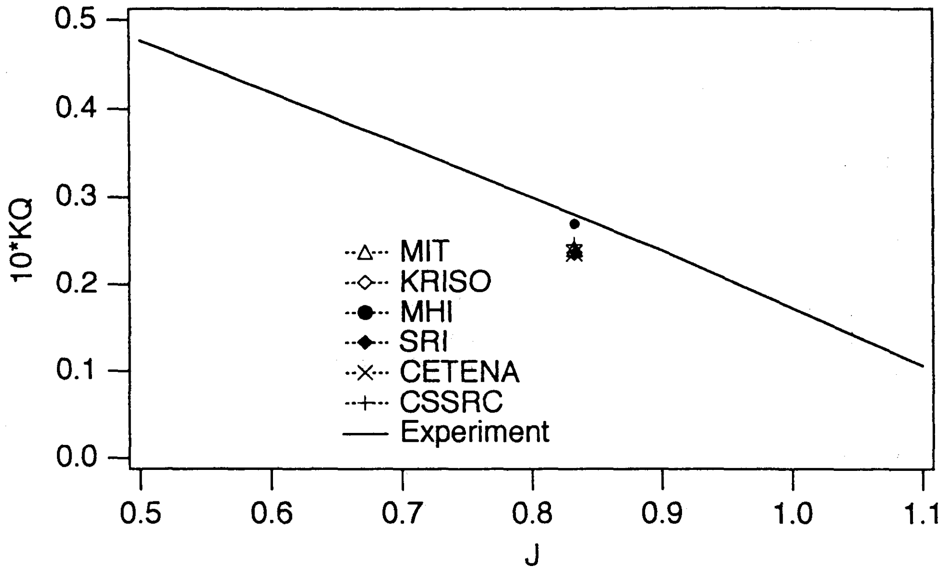

Fig.1.2.1(c) Case C , DTRC4119 , With Hub , Linear Wake
KQ Without Viscous Correction

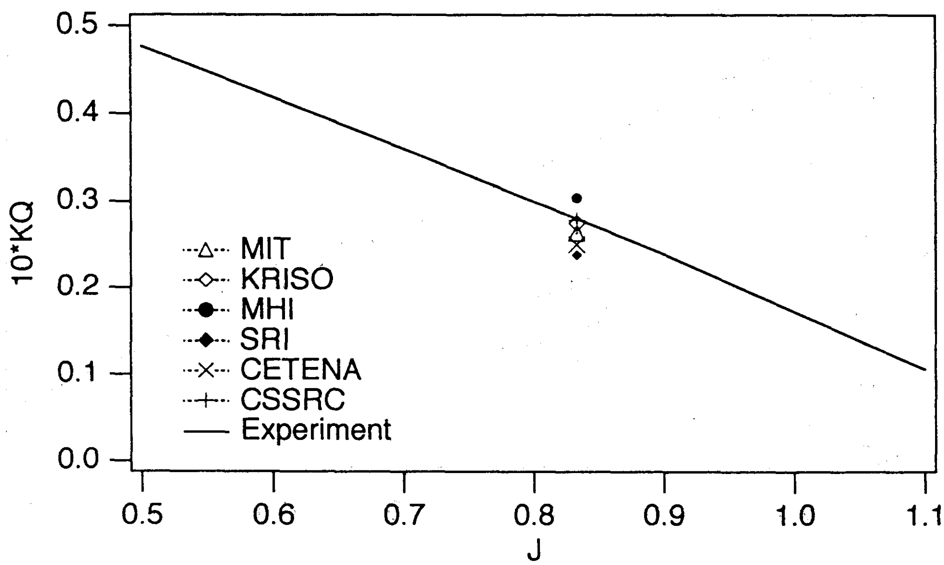

Fig.1.2.1(d) Case C , DTRC4119 , With Hub , Linear Wake
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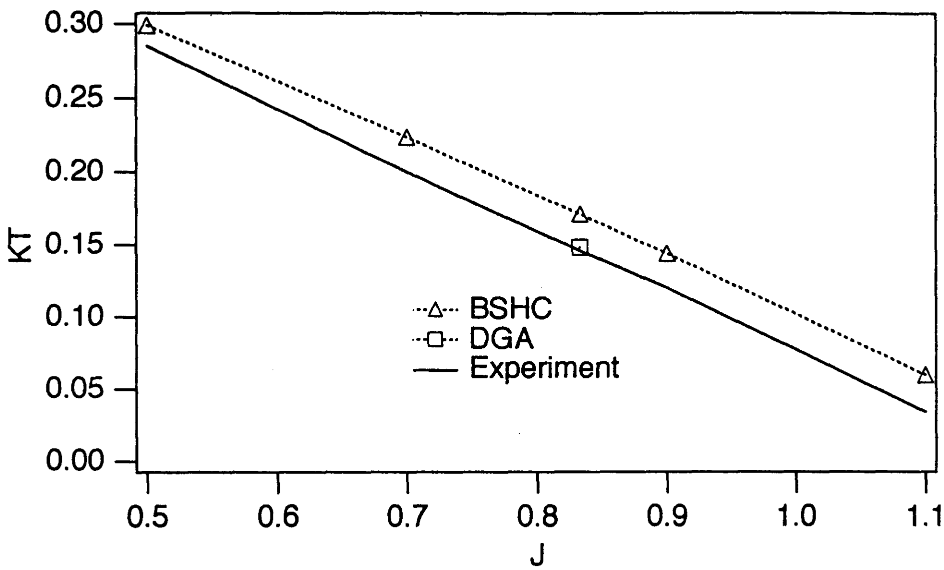

Fig.1.2.2(a) Case C , DTRC4119 , With Hub , Linear Wake
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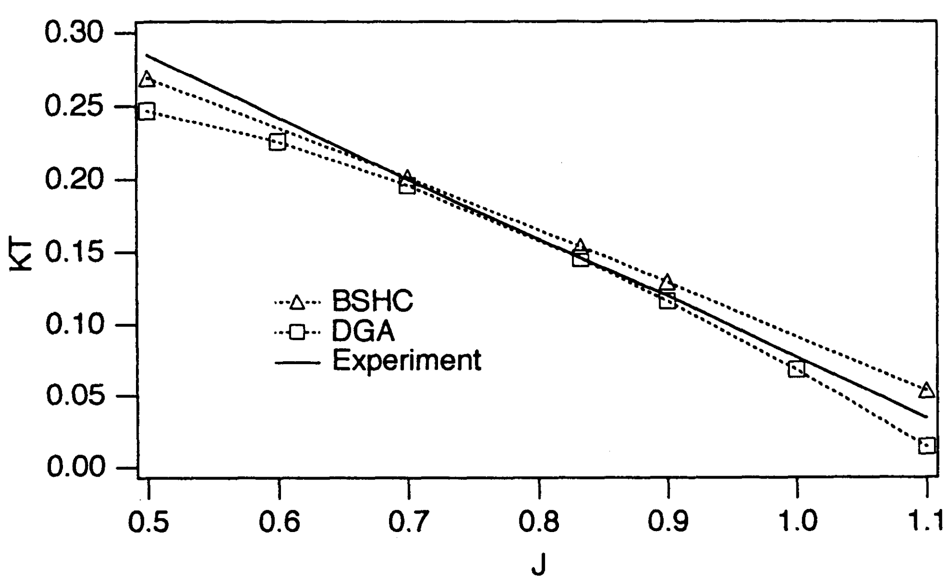
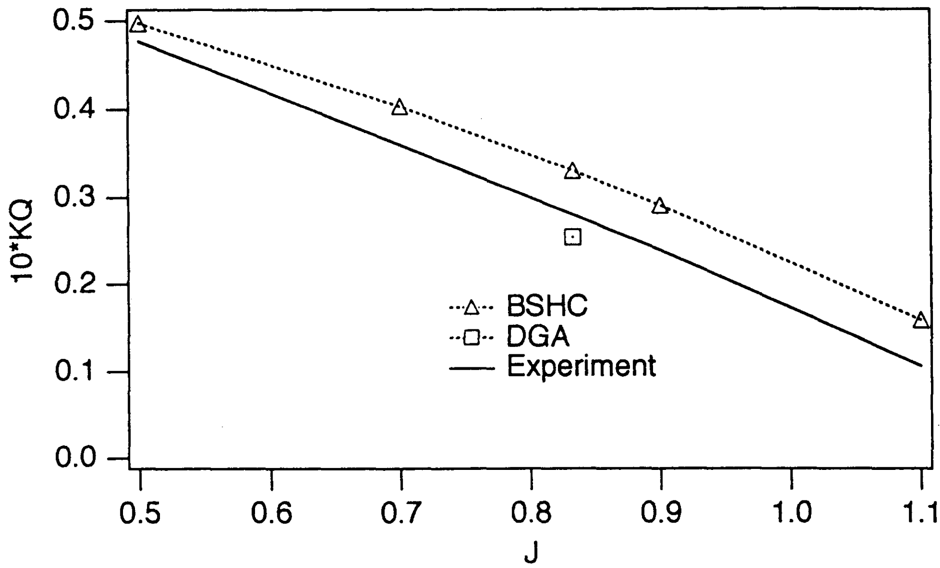


Fig.1.2.2 (b) Case C , DTRC4119 , With Hub , Linear Wake
KT With Viscous Correction



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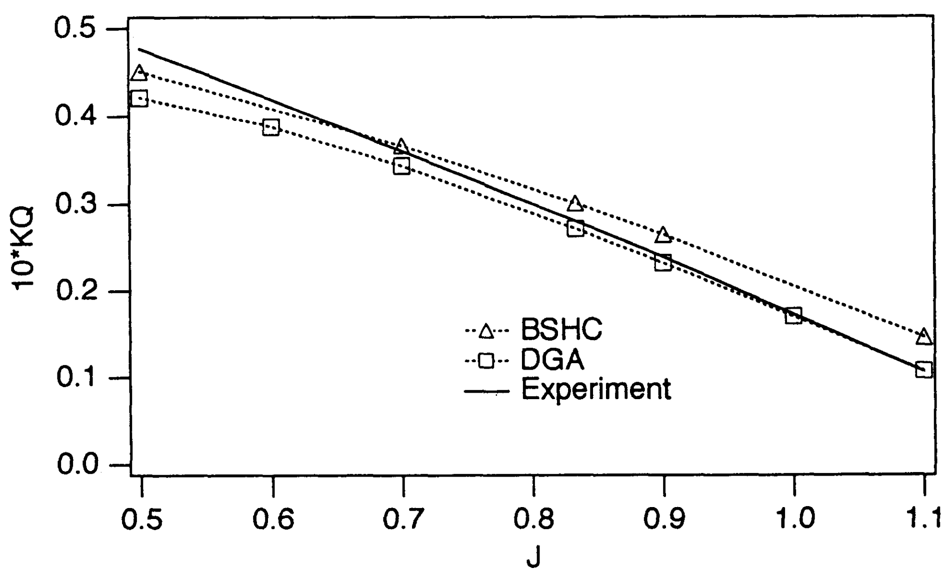

Fig.1.2.2 (d) Case C , DTRC4119 , With Hub , Linear Wake
KQ With Viscous Correction

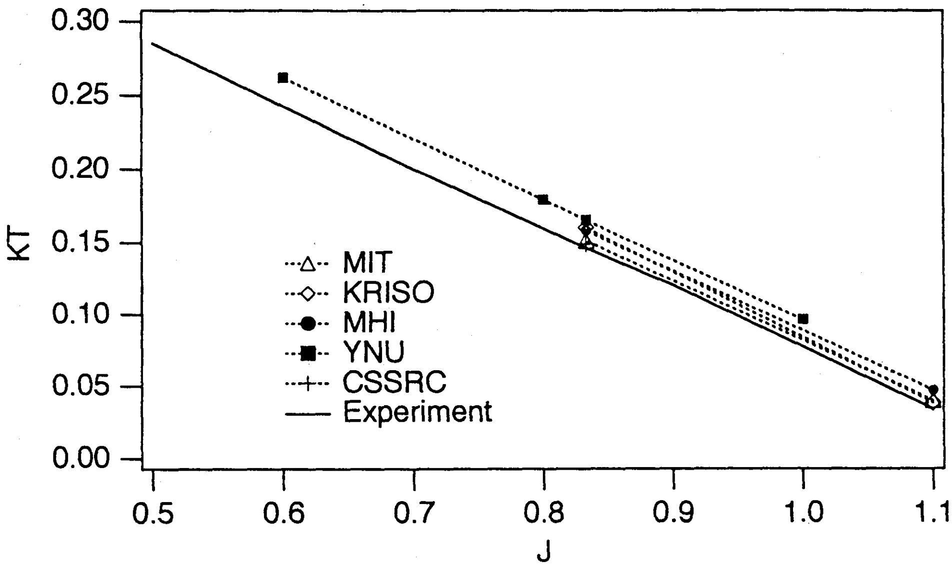

Fig.1.3.1(a) Case D , DTRC4119 , Without Hub , Devised Wake
KT Without Viscous Correction

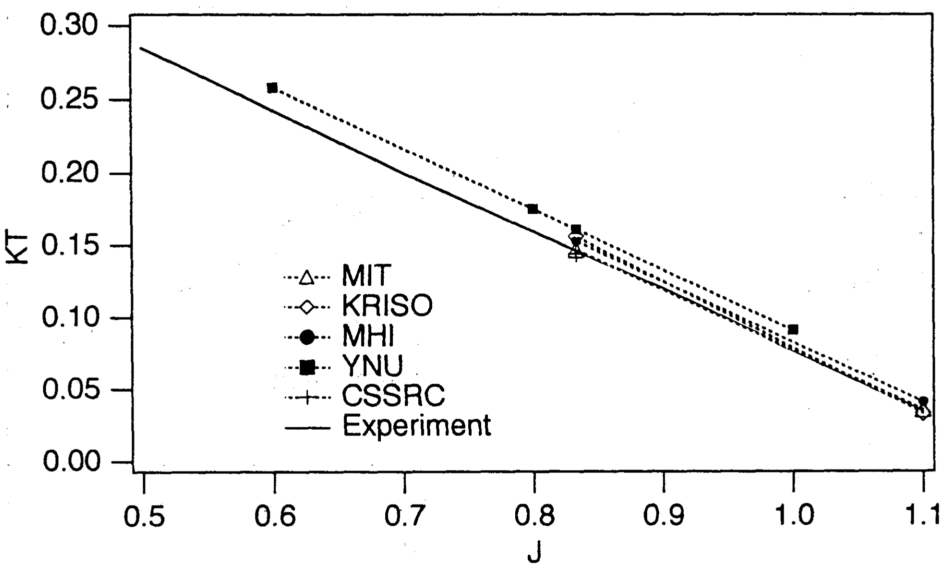

Fig.1.3.1(b) Case D, DTRC4119 , Without Hub , Devised Wake
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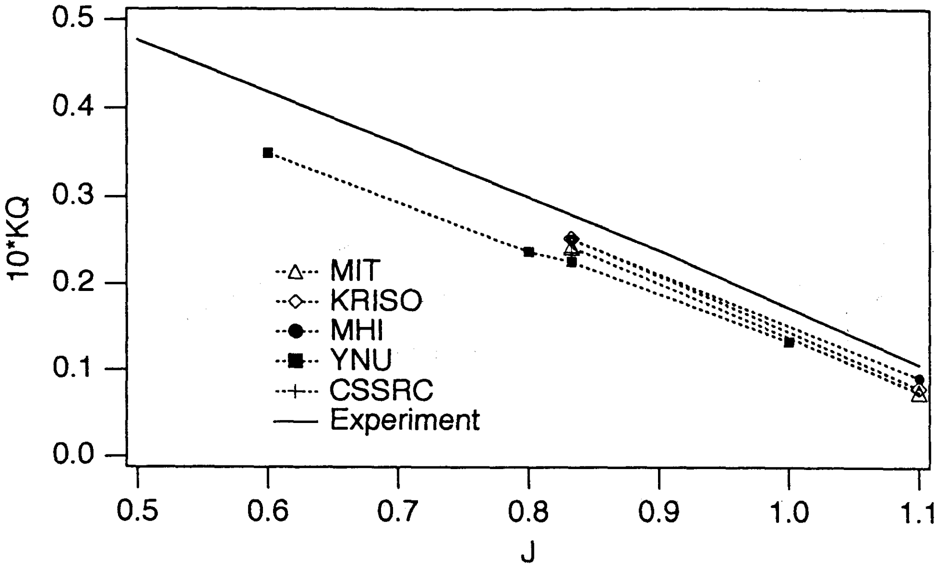

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KQ Without Viscous Correction

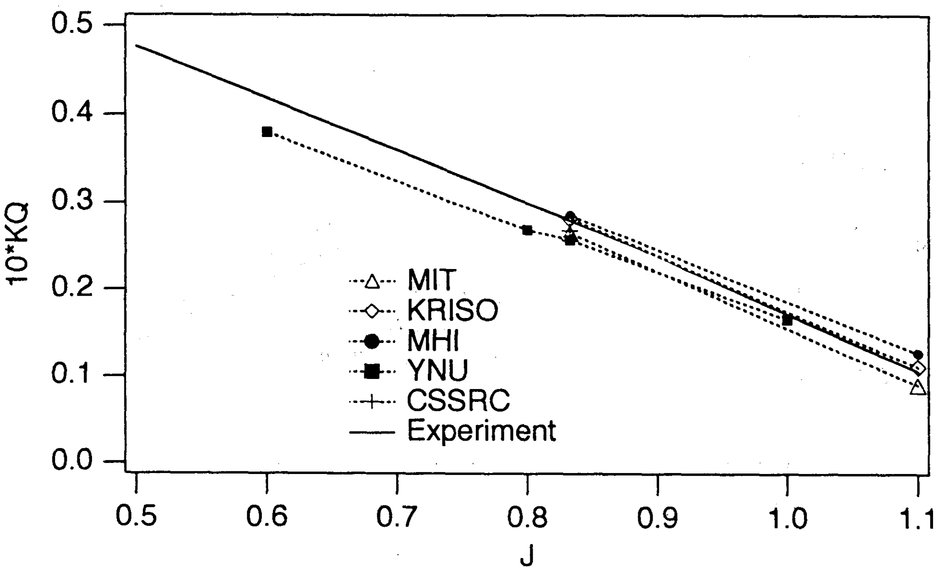


Fig.1.3.1(d) Case D , DTRC4119 , Without Hub , Devised Wake
KQ With Viscous Correction

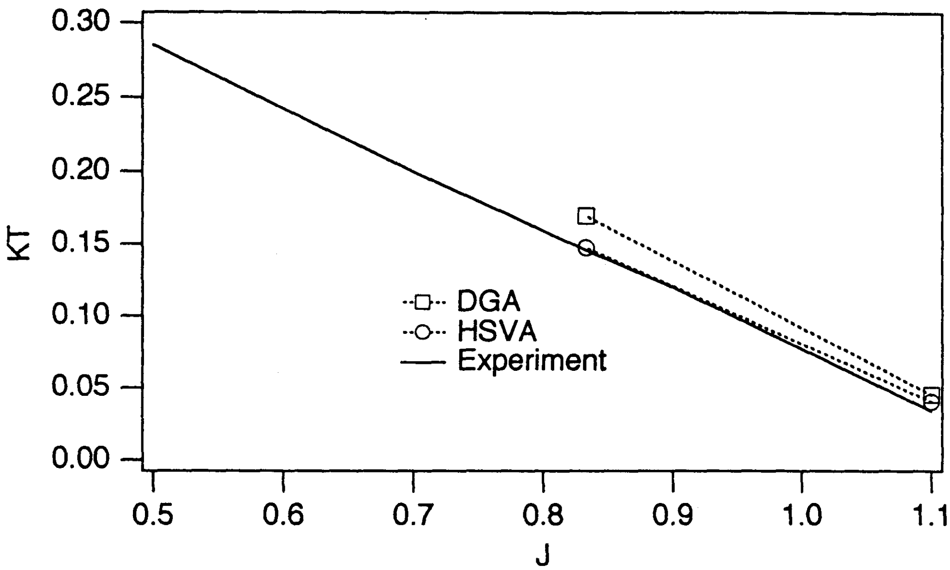
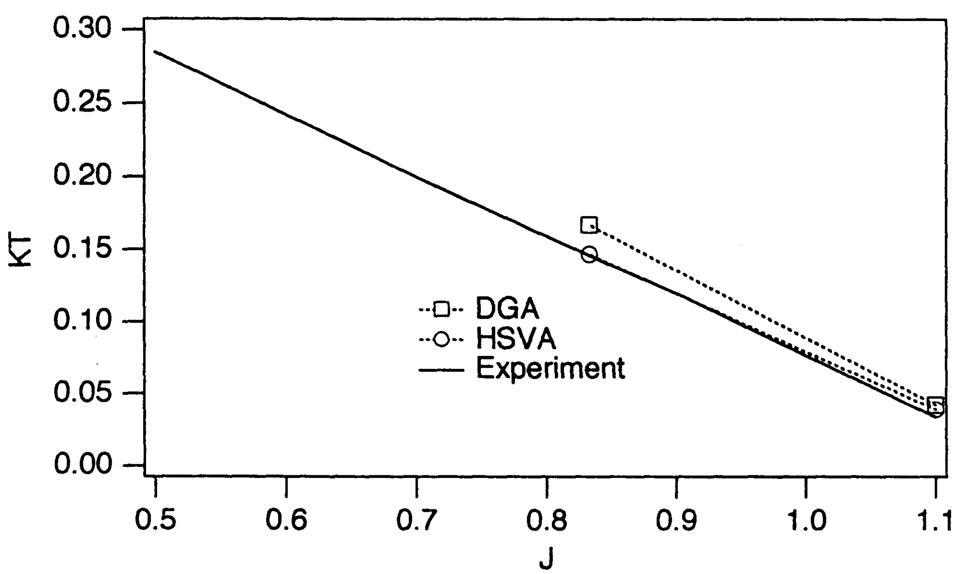


Fig.1.3.2(a) Case D, DTRC4119 , Without Hub , Devised Wake
KT Without Viscous Correction



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KT With Viscous Correction

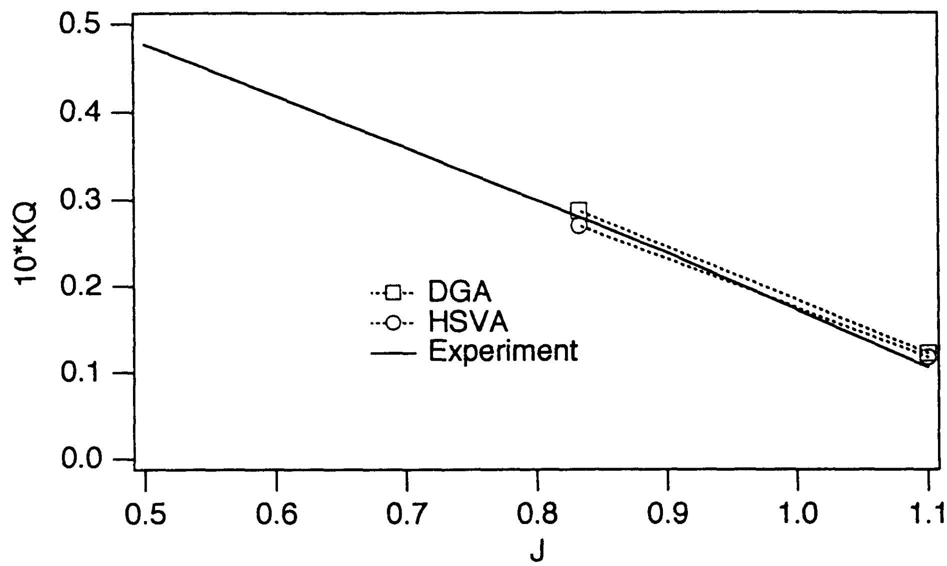


Fig.1.3.2(c) Case D, DTRC4119 , Without Hub , Devised Wake
KQ Without Viscous Correction

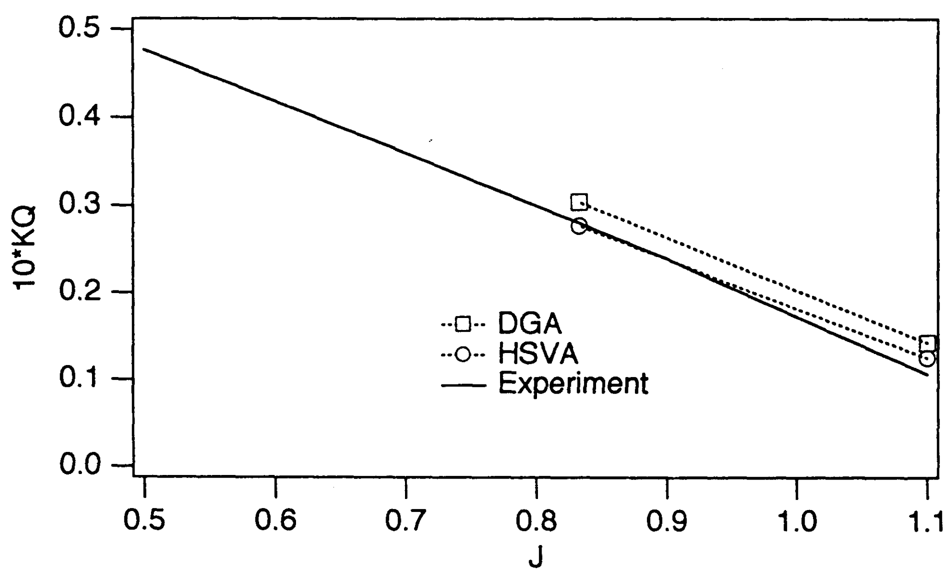


Fig.1.3.2(d) Case D , DTRC4119 , Without Hub , Devised Wake
KQ With Viscous Correction

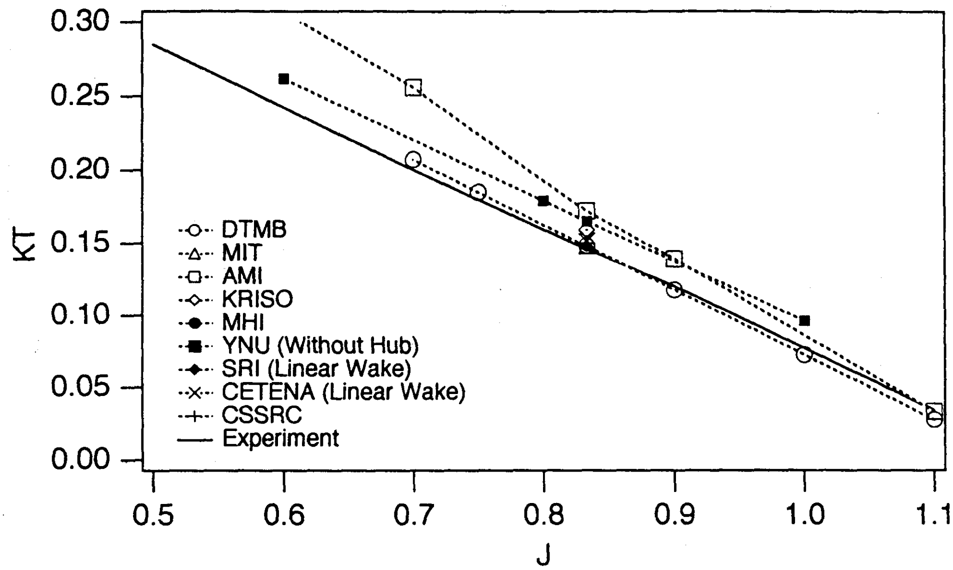


Fig. 1.4.1 (a) Case E , DTRC4119 , With Hub , Devised Wake
KT Without Viscous Correction

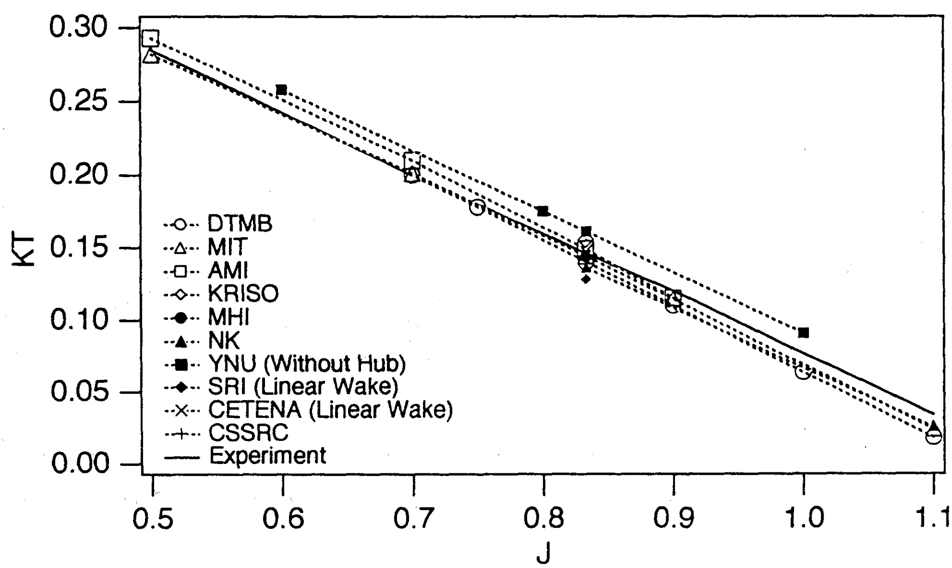


Fig. 1.4.1 (b) Case E , DTRC4119 , With Hub , Devised Wake
KT With Viscous Correction

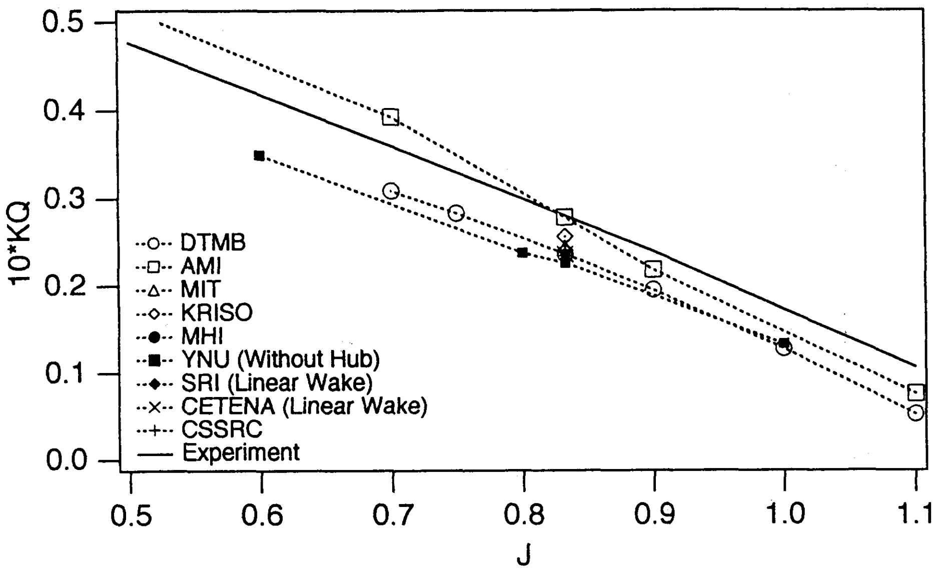


Fig. 1.4.1 (c) Case E , DTRC4119 , With Hub , Devised Wake
KQ Without Viscous Correction

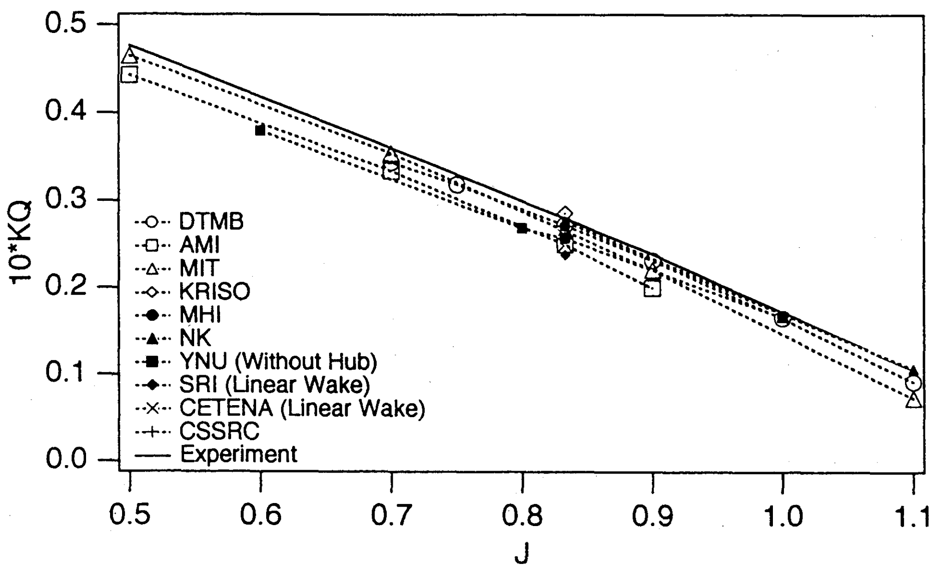


Fig. 1.4.1 (d) Case E , DTRC4119 , With Hub , Devised Wake
KQ With Viscous Correction

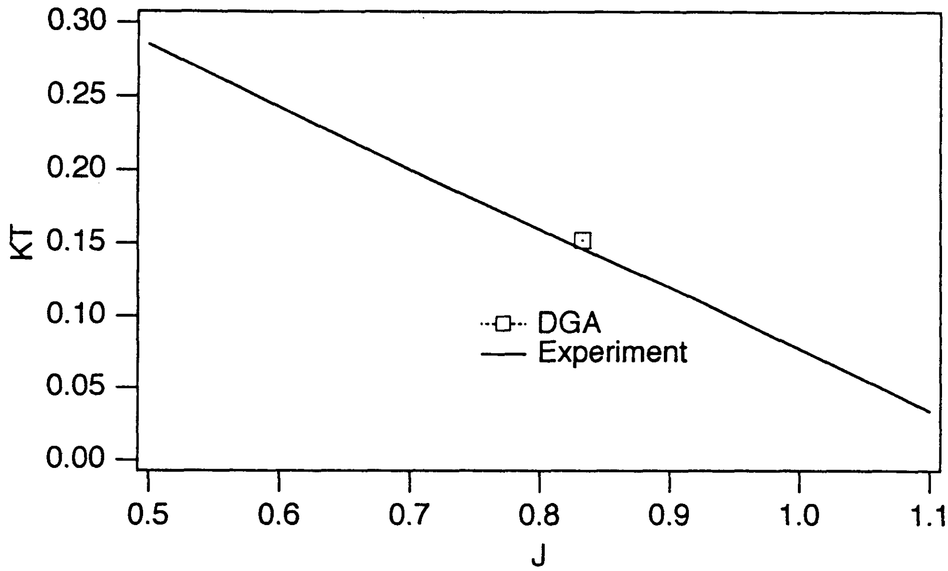
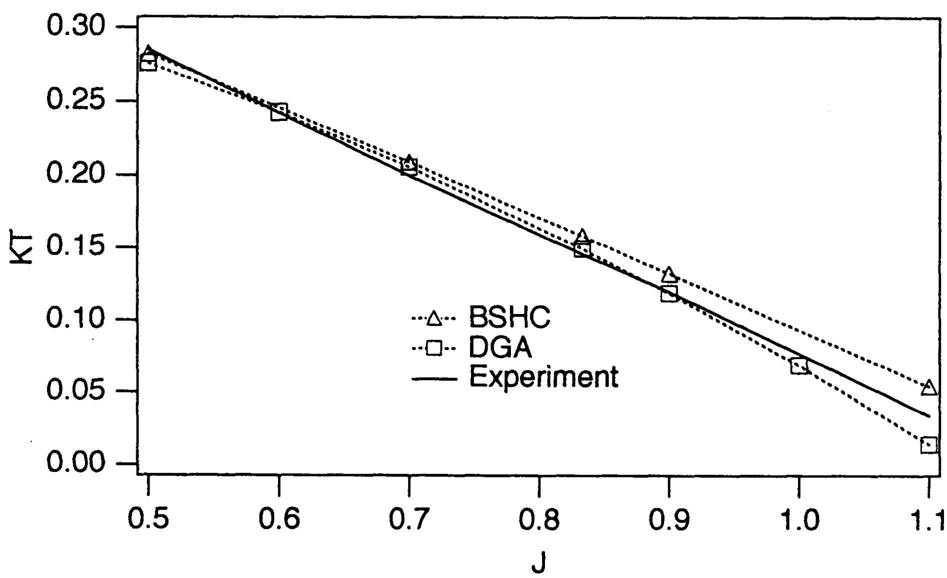


Fig.1.4.2 (a) Case E , DTRC4119 , With Hub , Devised Wake
KT Without Viscous Correction



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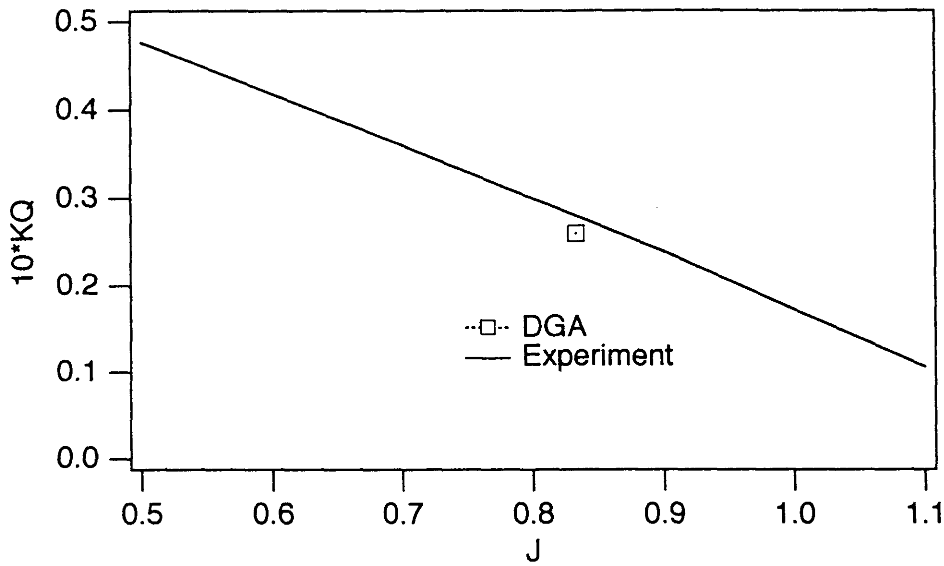
KT With viscous Correction



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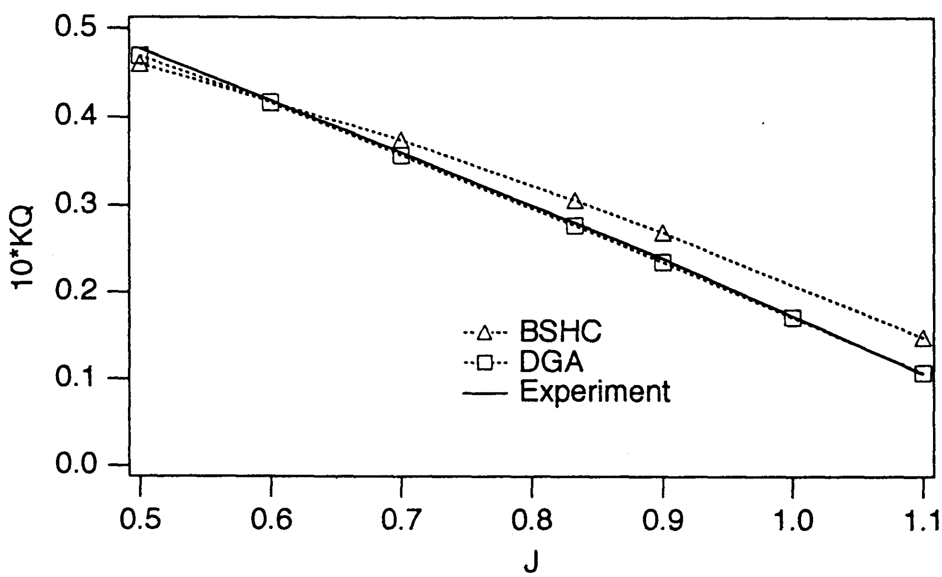

Fig.1.4.2 (d) Case E , DTRC4119 , With Hub , Devised Wake
KQ With Viscous Correction

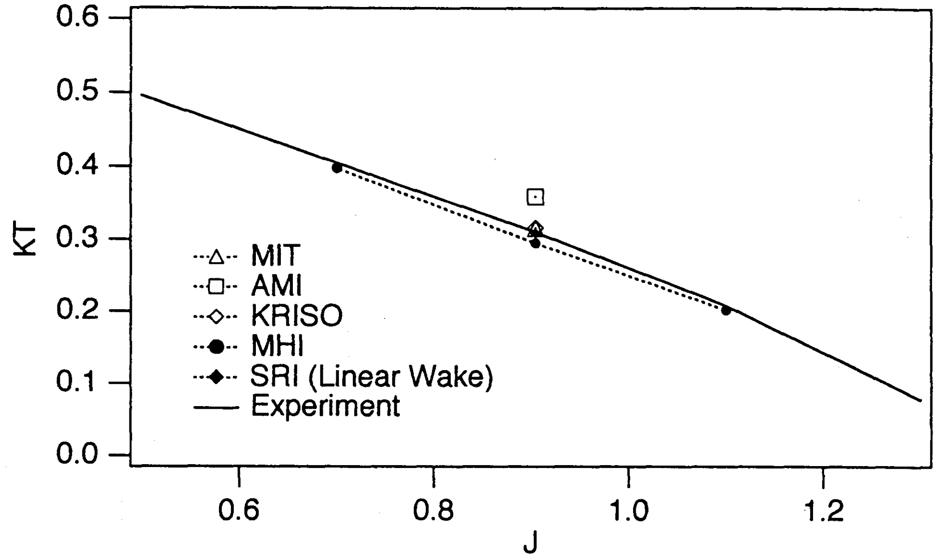

Fig. 1.5.1 (a) Case H , DTRC4842 , With Hub , Devised Wake
KT Without Viscous Correction

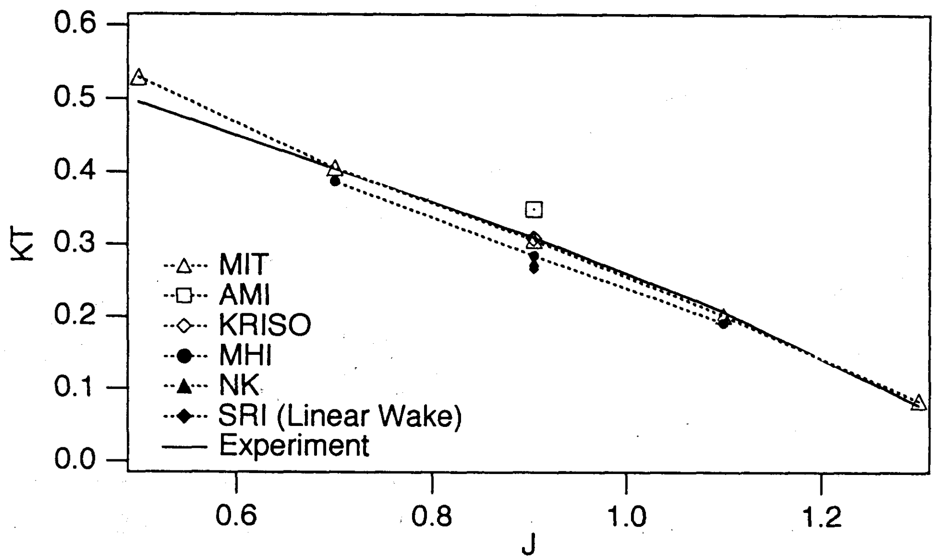

Fig. 1.5.1 (b) Case H , DTRC4842 , With Hub , Devised Wake
KT With Viscous Correction

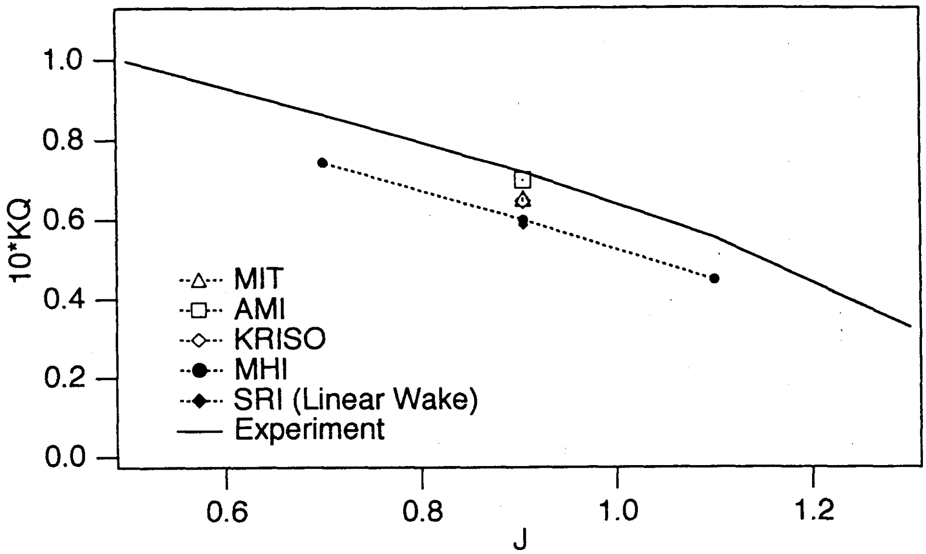

Fig. 1.5.1 (c) Case H , DTRC4842 , With Hub , Devised Wake
KQ Without Viscous Correction

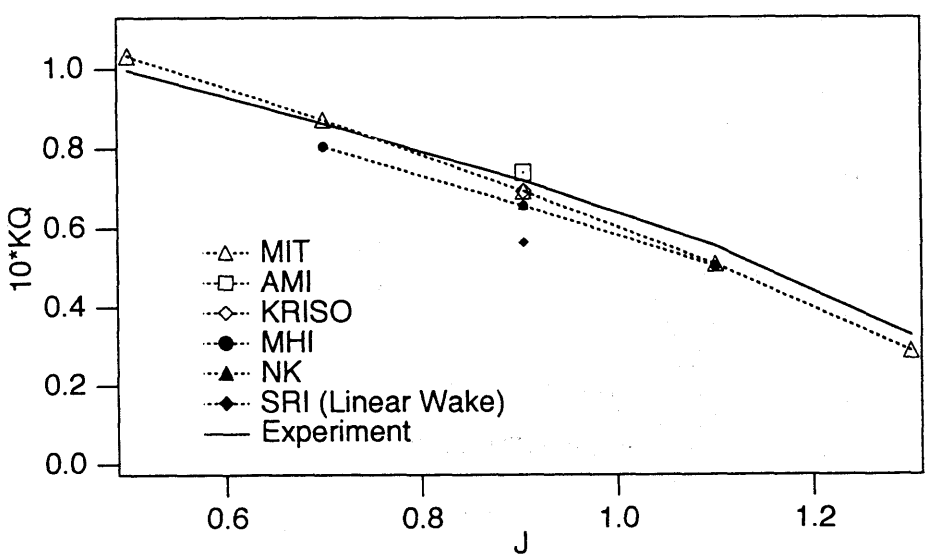

Fig.1.5.1(d) Case H , DTRC4842 , With Hub , Devised Wake
KQ With Viscous Correction

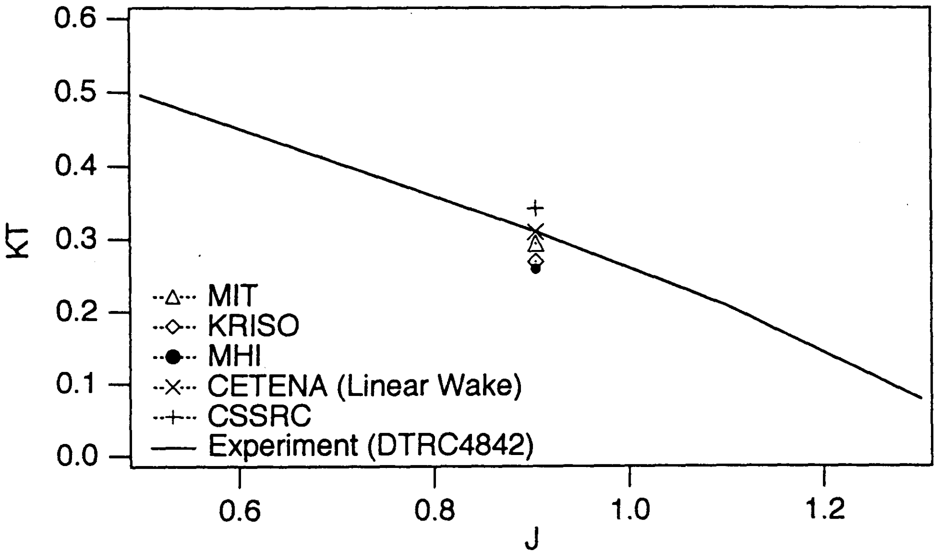

Fig.1.6.1(a) Case I , DTRC4842I , With Hub , Devised Wake
KT Without Viscous Correction

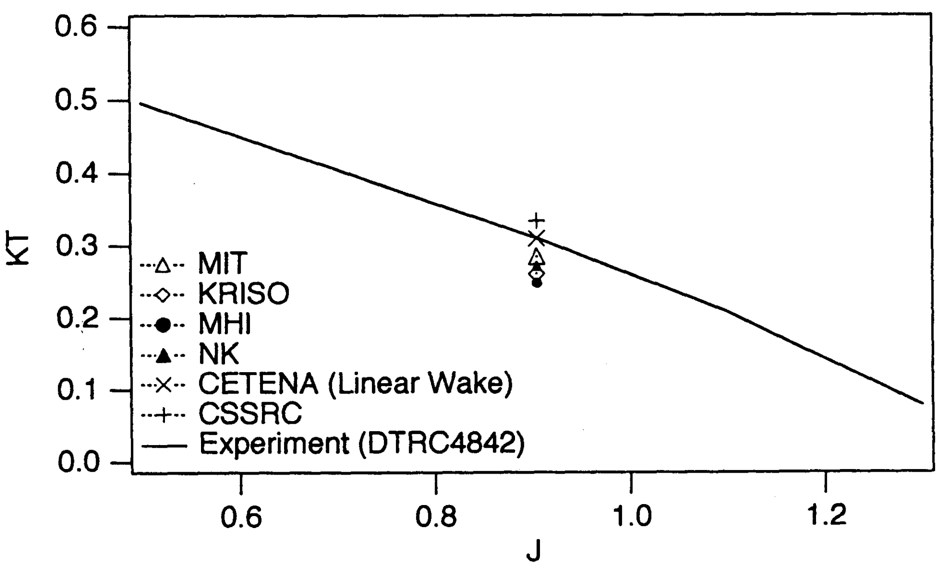

Fig.1.6.1(b) Case I , DTRC4842I , With Hub , Devised Wake
KT With Viscous Correction

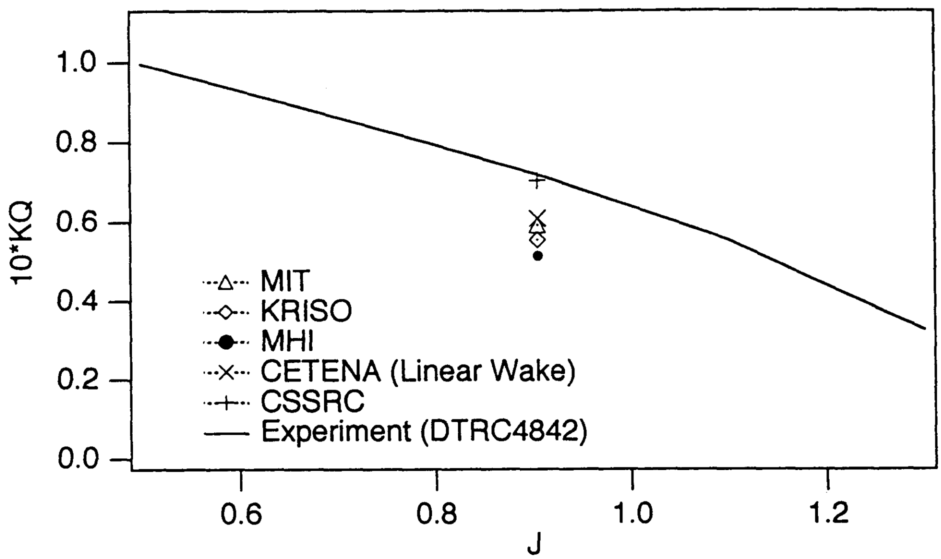

Fig.1.6.1(c) Case I , DTRC4842I , With Hub , Devised Wake
KQ Without Viscous Correction

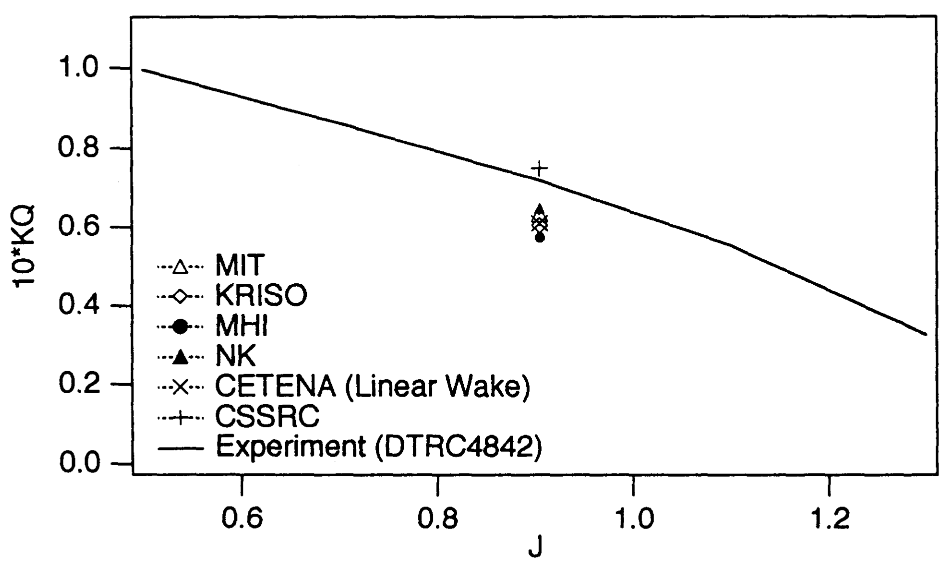

Fig.1.6.1(d) Case I , DTRC4842I , With Hub , Devised Wake
KQ With Viscous Correction