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IGNITION TRANSIENT CALCULATIONS IN THE SPACE SHUTTLE SOLID ROCKET MOTOR

Rhonald M. Jenkins and Winfred A. Foster, Jr.

Aerospace Engineering Department
Auburn University, Alabama

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ABSTRACT

The work presented is part of an effort to develop a multi-dimensional ignition transient model for large solid propellant rocket motors. On the Space Shuttle, the ignition transient in the slot is induced when the igniter, itself a small rocket motor, is fired into the head-end portion of the main rocket motor. The computational results presented in this paper consider two different igniter configurations. The first configuration is a simulated Space Shuttle RSRM igniter which has one central nozzle that is parallel to the centerline of the motor. The second igniter configuration has a nozzle which is canted at an angle of 45° from the centerline of the motor. This paper presents a computational fluid dynamic (CFD) analyses of certain flow field characteristics inside the solid propellant star grain slot of the Space Shuttle during the ignition transient period of operation for each igniter configuration. The majority of studies made to date regarding ignition transient performance in solid rocket motors have concluded that the key parameter to be determined is the heat transfer rate to the propellant surface and hence the heat transfer coefficient between the gas and the propellant. In this paper the heat transfer coefficients, pressure and velocity distributions are calculated in the star slot. In order to validate the computational method and to attempt to establish a correlation between the flow field characteristics and the heat transfer rates a series of cold flow experimental investigations were conducted. The results of these experiments show excellent qualitative and quantitative agreement with the pressure and velocity distributions obtained from the CFD analysis. The CFD analysis utilized a classical pipe flow type correlation for the heat transfer rates. The experimental results provide an excellent qualitative comparison with regard to spatial distribution of the heat transfer rates as a function of nozzle configuration and igniter pressure. The results indicate that from a quantitative point of view that the pipe flow correlation gives reasonably good results. Furthermore, there appears to be a direct correlation between igniter pressure and an average Reynolds number in the star grain slot. This may lead to a simple method for modifying the convection heat transfer correlation. Calculated results of pressure-vs-time for the first 200 msec of motor firing of the Space Shuttle RSRM support the trends shown for the heat transfer rate comparisons between the cold flow CFD and experimental data.

ACKNOWLEDGEMENTS

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In particular, the assistance of John E. Hengel and Andrew W. Smith is acknowledged.

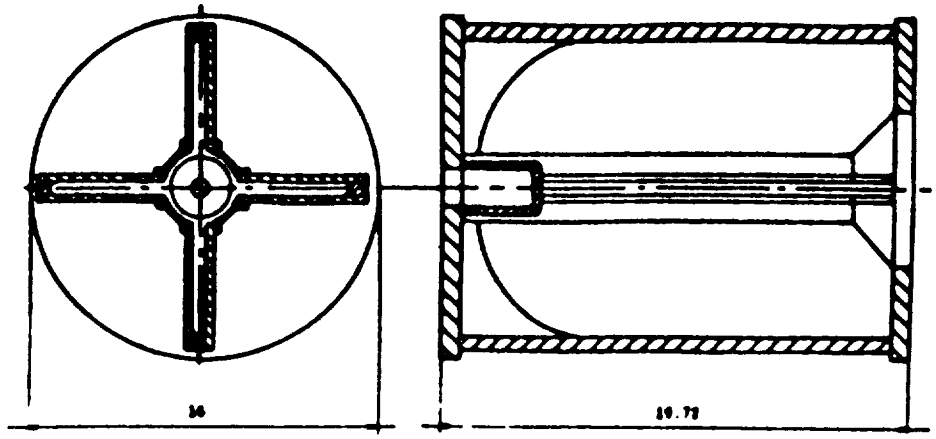
OUTLINE

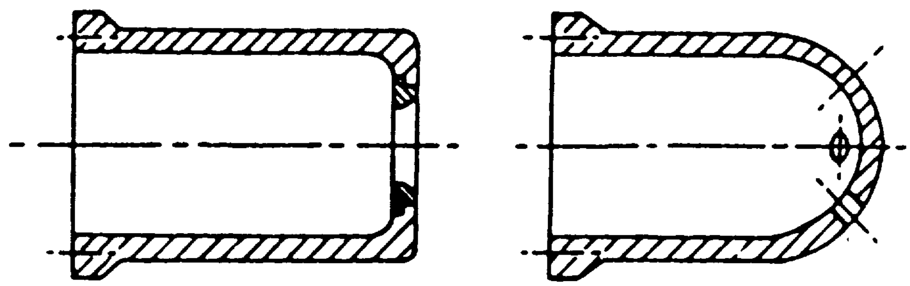
Presentation of Cold-Flow Heat Transfer/ Aerodynamic Results for Flow in the Head-End Star Slot of the Space Shuttle SRM

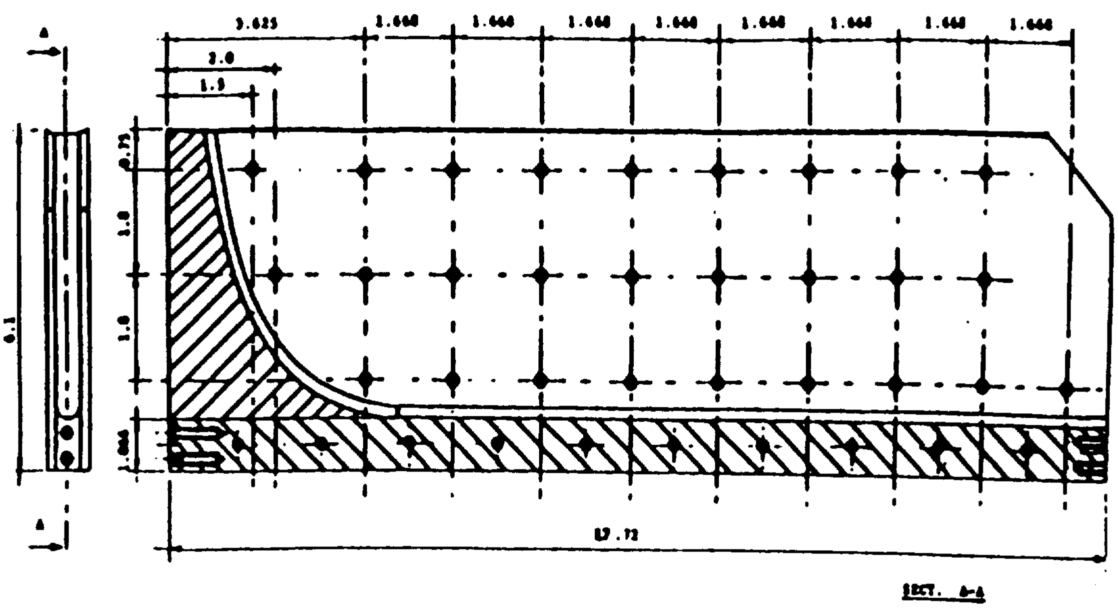
- Single Port Igniter
- 45° Igniter (no center port)

Presentation of Flow Visualization Results for Three Igniter Configurations

- Single Port Igniter
- 45° Igniter (no center port)
- 45° Igniter (with center port)







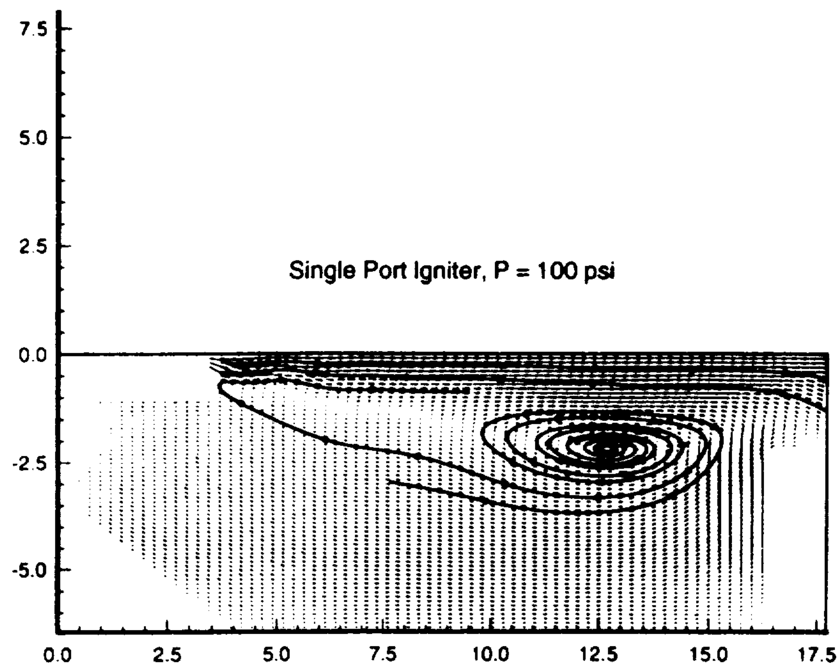
HEAT TRANSFER MODEL

Heat transfer from gas to wall is assumed to be by convection only.

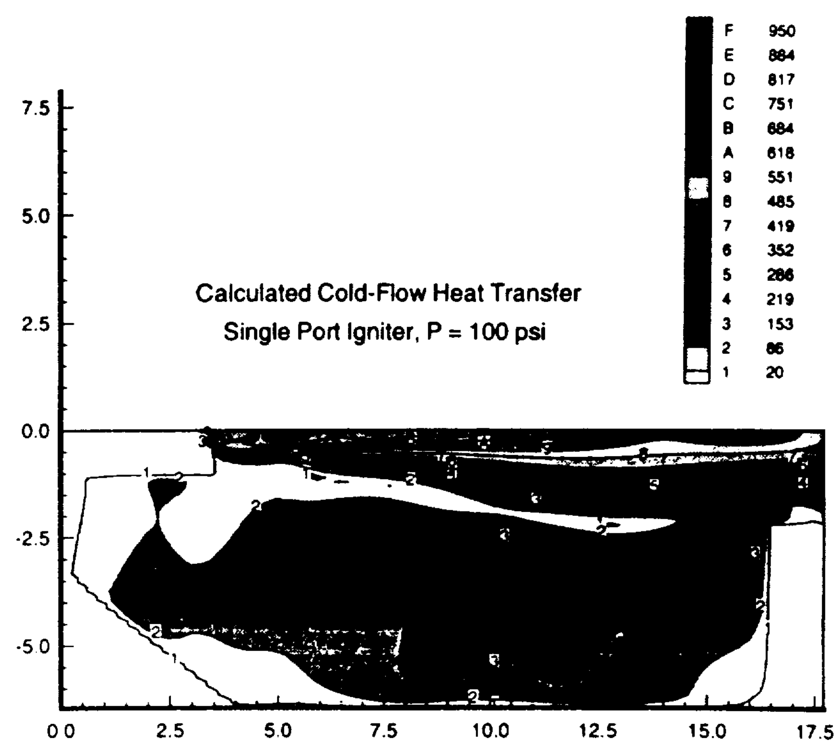
The convection correlation utilized was originally derived for turbulent pipe flow, but can be adapted to arbitrary geometries. The correlation utilized is of the form

$$Nu = \frac{0.152Re^{0.9}Pr}{0.833[2.25\ln(0.114Re^{0.9}) + 13.2Pr - 5.8]}$$

where Re is based on the hydraulic diameter of the slot.



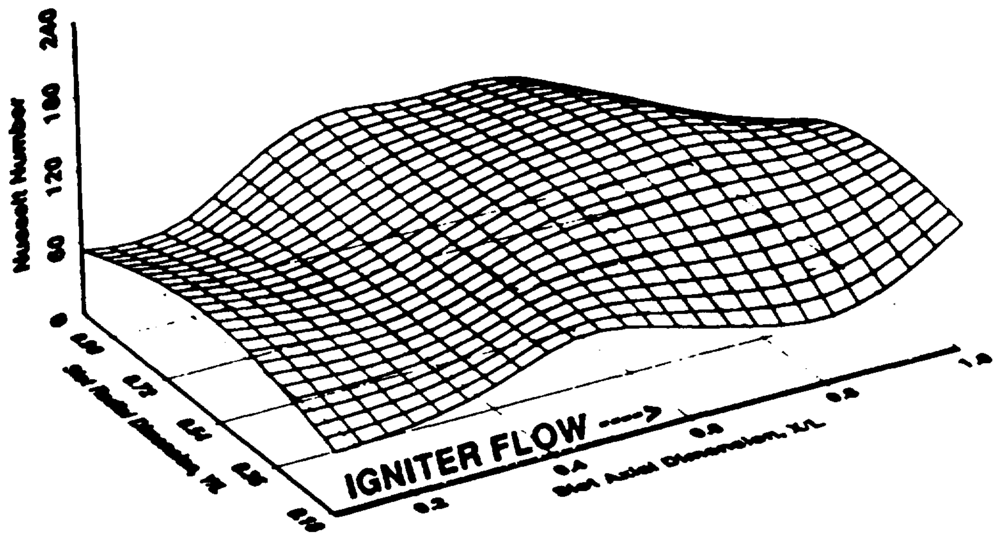
Single Port Igniter, P = 100 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5



F 950
E 884
D 817
C 751
B 684
A 618
9 551
8 485
7 419
6 352
5 286
4 219
3 153
2 86
1 20
Calculated Cold-Flow Heat Transfer
Single Port Igniter, P = 100 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5

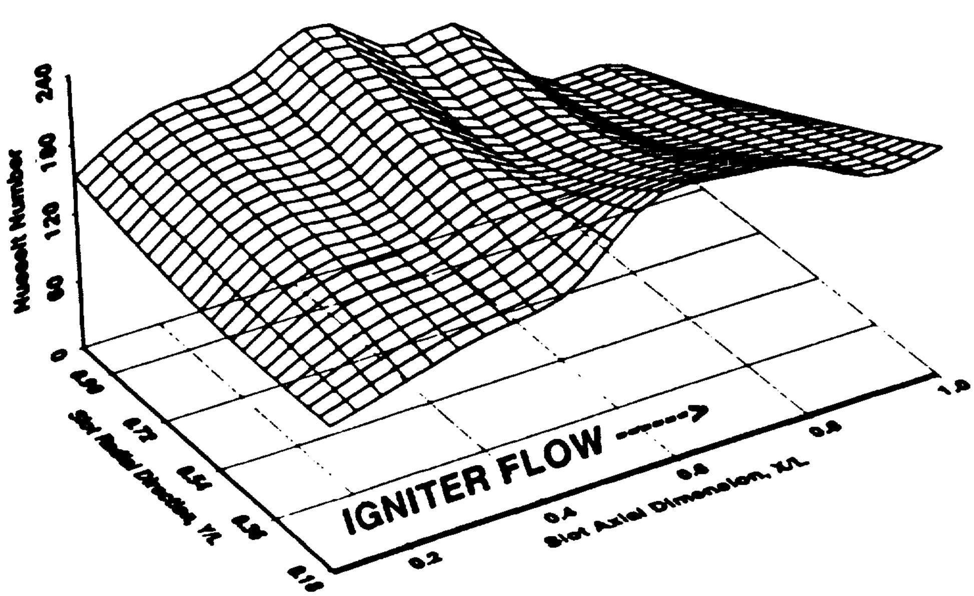
Calculated Heat Transfer, Single Port Igniter

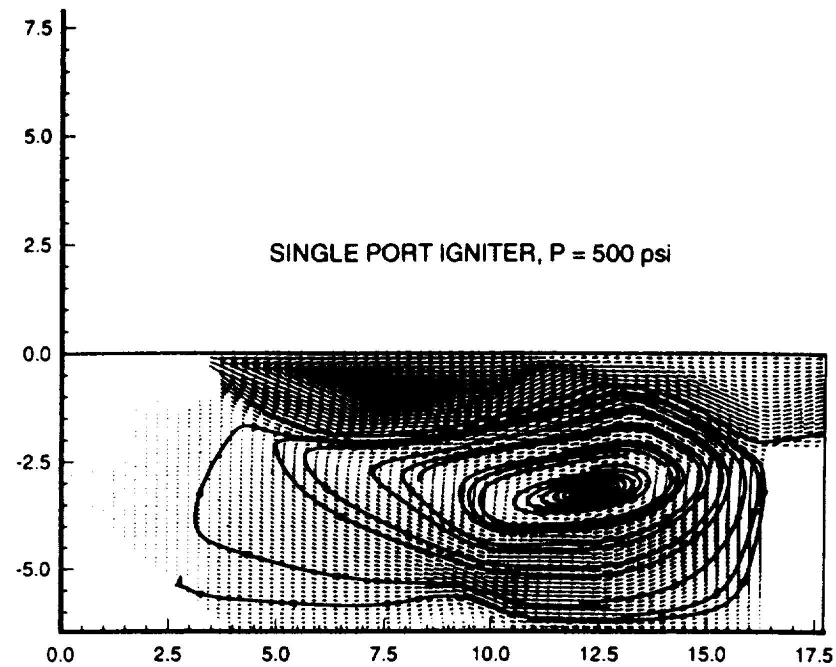
$P_{Igniter}$ = 100 psi

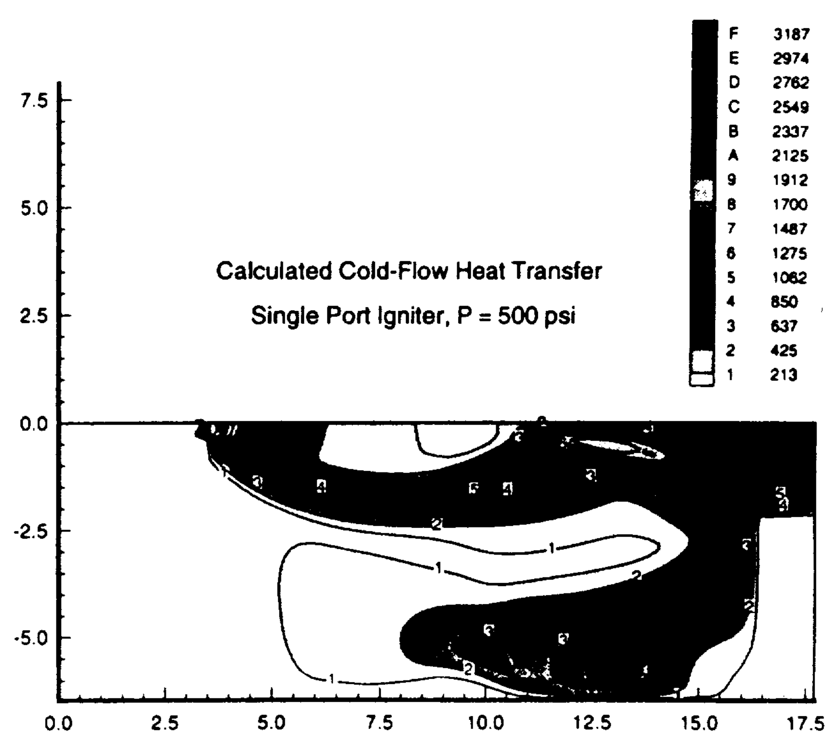


Measured Heat Transfer, Single Port Igniter

$P_{Igniter}$ = 100 psi

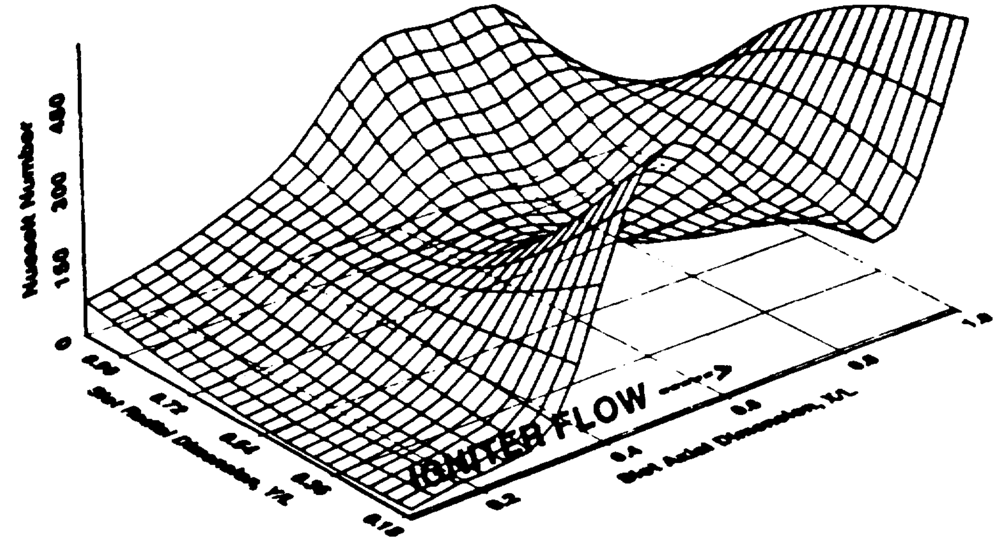



SINGLE PORT IGNITER, P = 500 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5


Calculated Cold-Flow Heat Transfer
Single Port Igniter, P = 500 psi
F 3187
E 2974
D 2762
C 2549
B 2337
A 2125
9 1912
8 1700
7 1487
6 1275
5 1062
4 850
3 637
2 425
1 213
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5

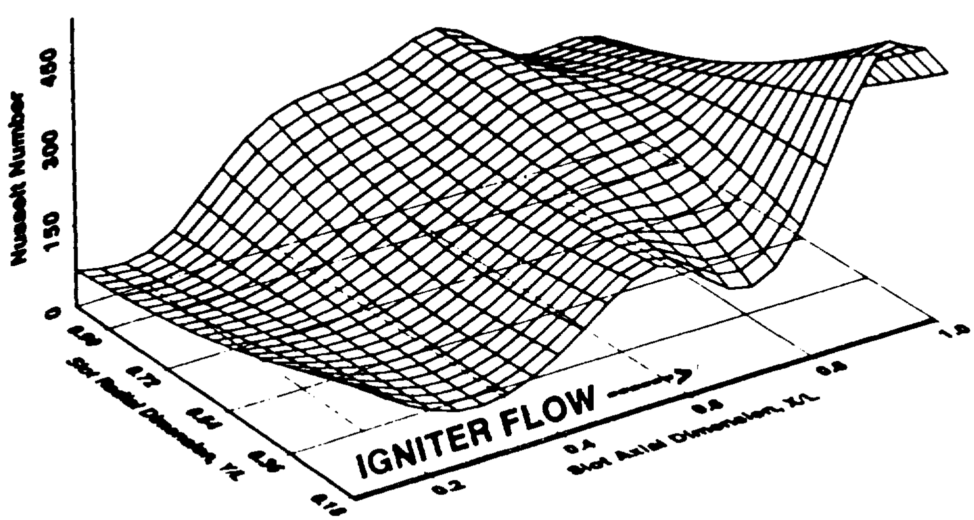
Calculated Heat Transfer, Single Port Igniter

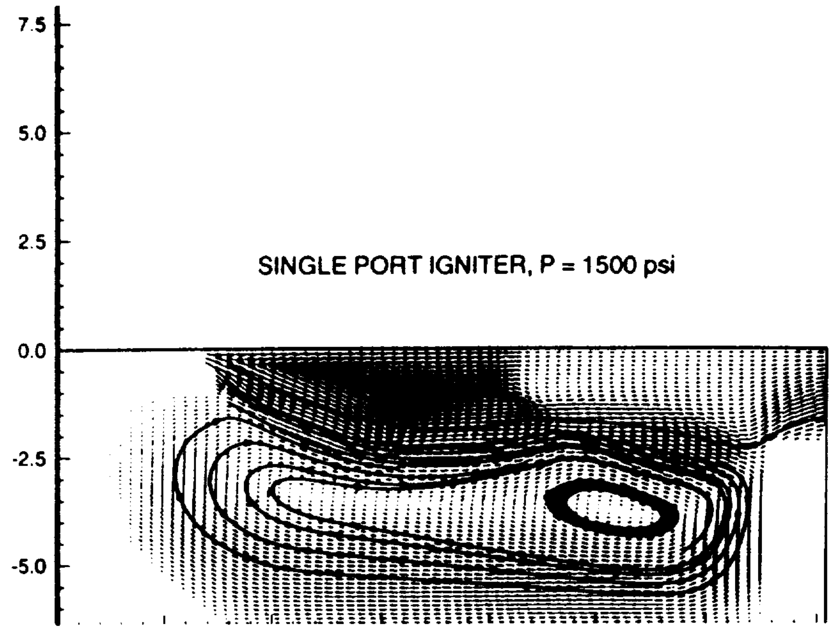
$P_{Igniter}$ = 500 psi

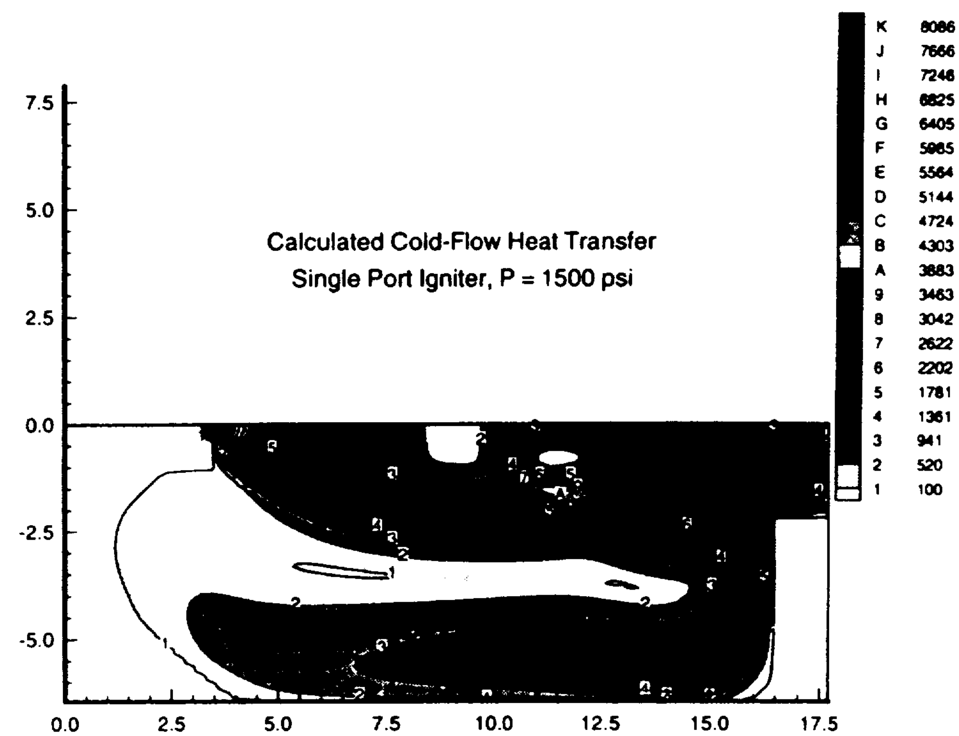


Measured Heat Transfer, Single Port Igniter

$P_{Igniter}$ = 500 psi

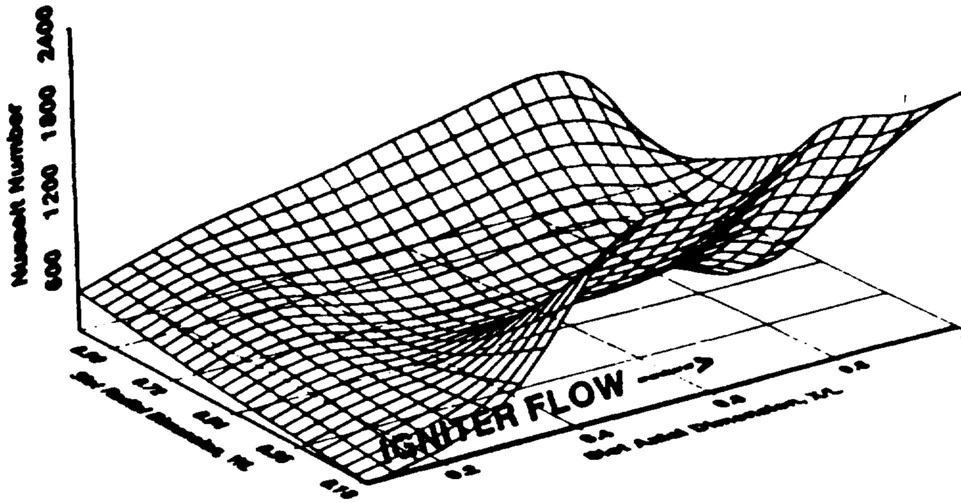



SINGLE PORT IGNITER, P = 1500 psi
7.5
5.0
2.5
0.0
-2.5
-5.0


Calculated Cold-Flow Heat Transfer
Single Port Igniter, P = 1500 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
K 8086
J 7666
I 7248
H 6825
G 6405
F 5985
E 5564
D 5144
C 4724
B 4303
A 3883
9 3463
8 3042
7 2622
6 2202
5 1781
4 1361
3 941
2 520
1 100

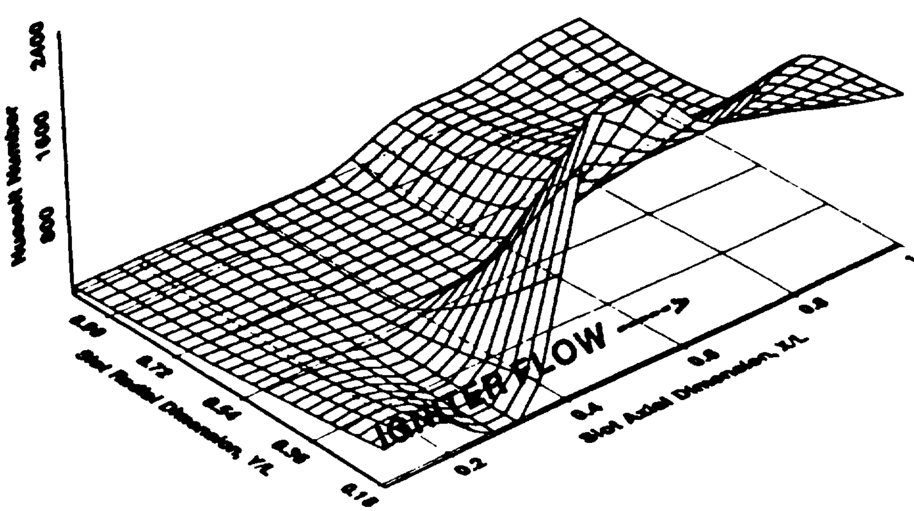
Calculated Heat Transfer, Single Port Igniter

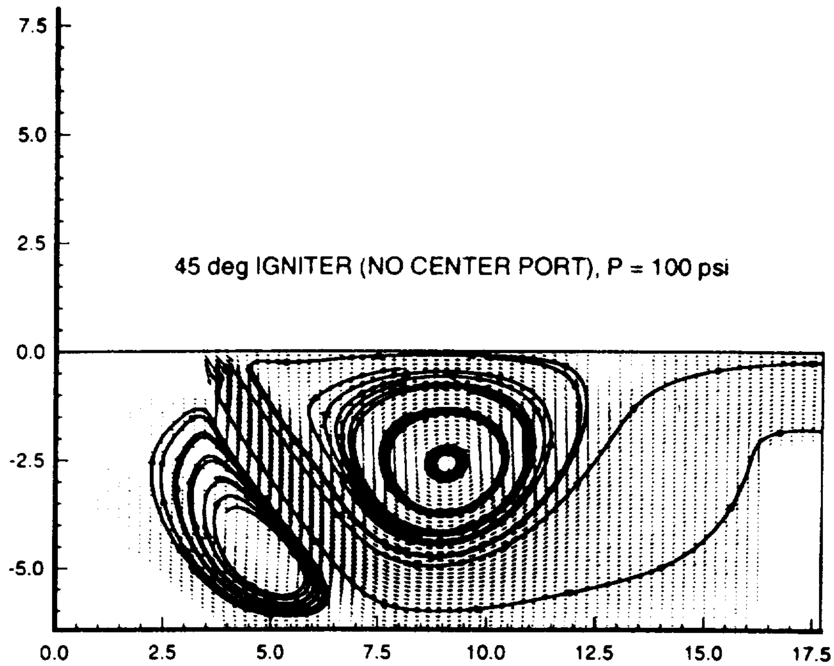
$P_{Igniter}$ = 1500 psi

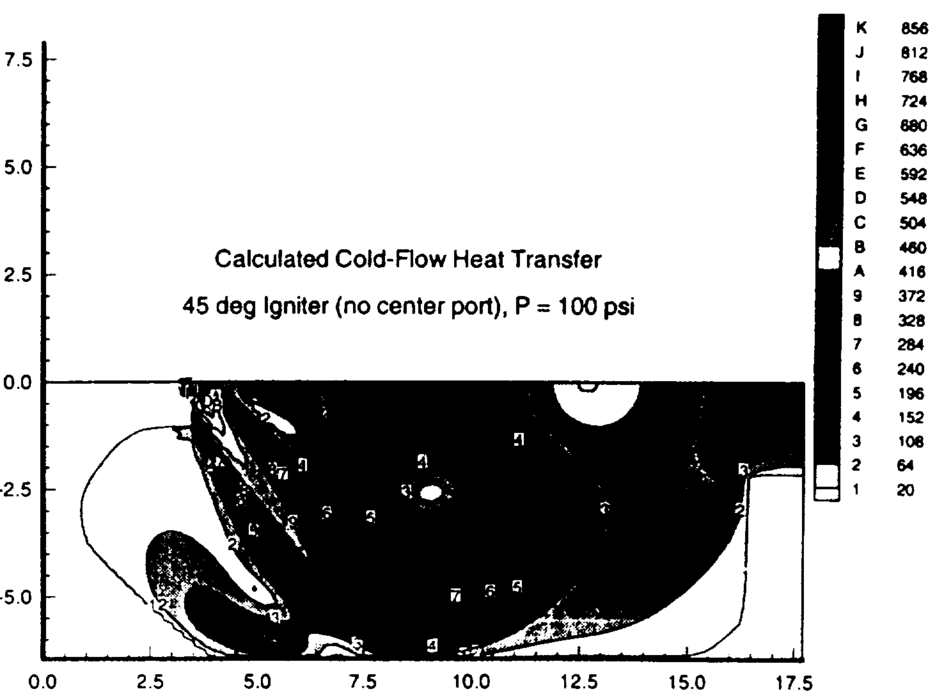


Measured Heat Transfer, Single Port Igniter

$P_{Igniter}$ = 1500 psi

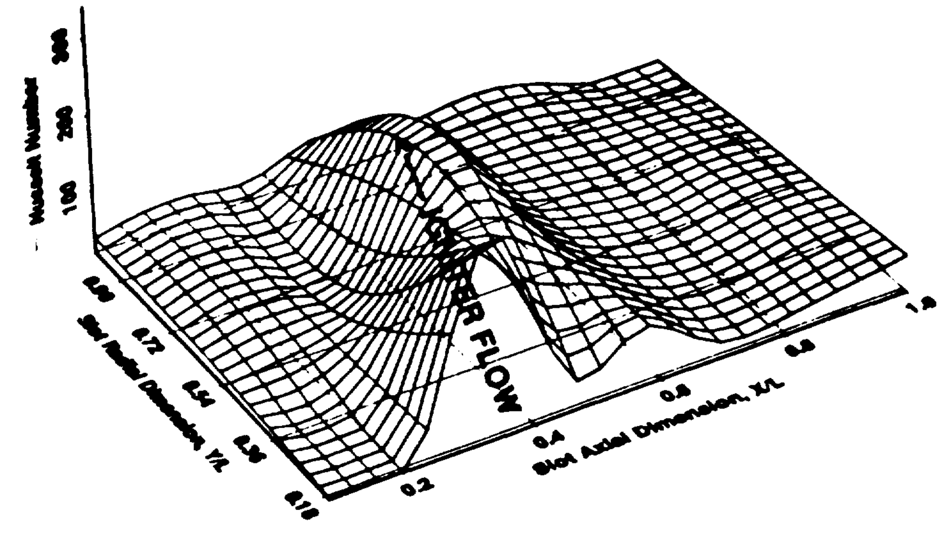



45 deg IGNITER (NO CENTER PORT), P = 100 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5


Calculated Cold-Flow Heat Transfer
45 deg Igniter (no center port), P = 100 psi
K 856
J 812
I 768
H 724
G 680
F 636
E 592
D 548
C 504
B 460
A 416
9 372
8 328
7 284
6 240
5 196
4 152
3 108
2 64
1 20
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5

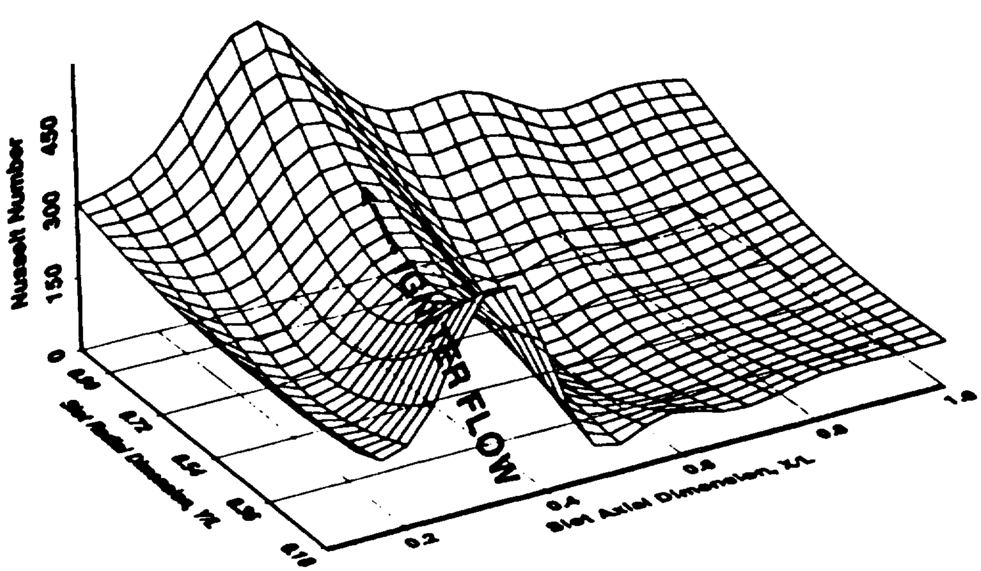
Calculated Heat Transfer, 45° Igniter

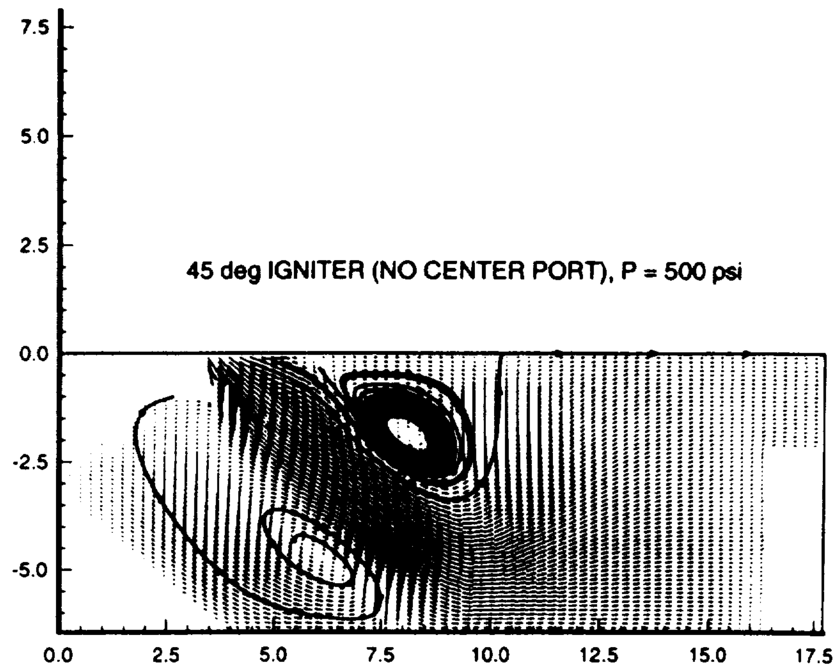
$P_{Igniter} = 100$ psi

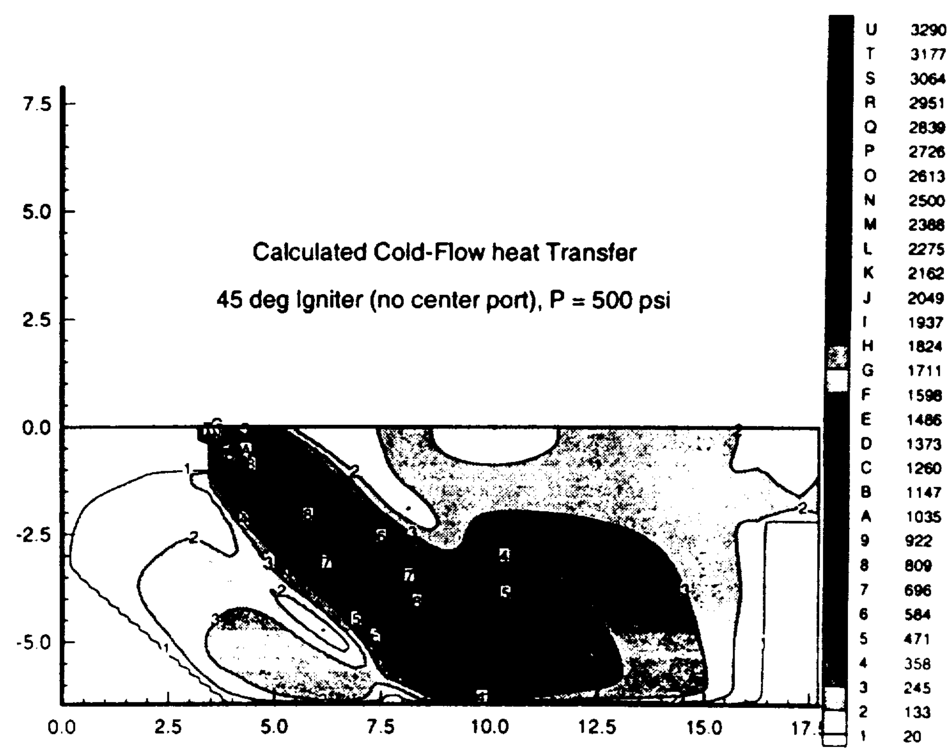


Measured Heat Transfer, 45° Igniter

$P_{Igniter} = 100$ psi

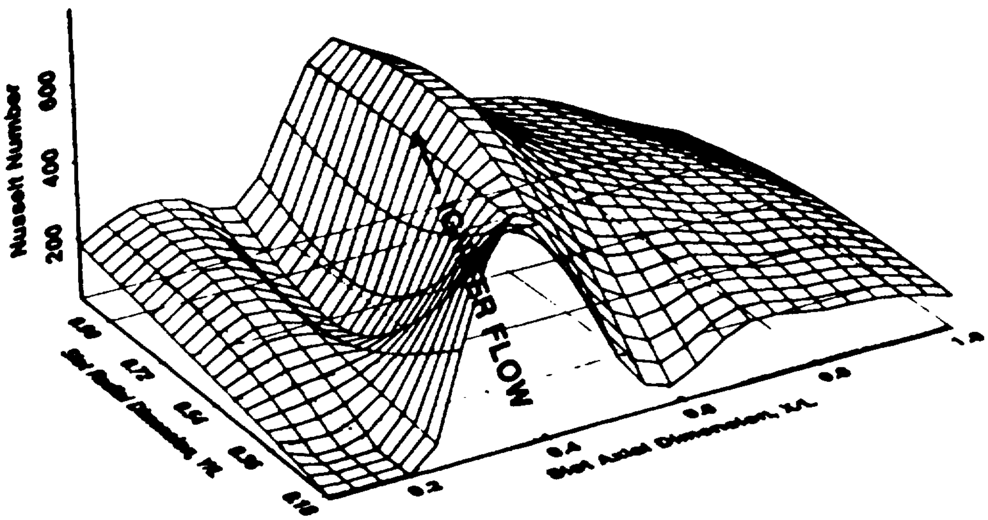



45 deg IGNITER (NO CENTER PORT), P = 500 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5


Calculated Cold-Flow heat Transfer
45 deg Igniter (no center port), P = 500 psi
U 3290
T 3177
S 3064
R 2951
Q 2839
P 2726
O 2613
N 2500
M 2388
L 2275
K 2162
J 2049
I 1937
H 1824
G 1711
F 1598
E 1486
D 1373
C 1260
B 1147
A 1035
9 922
8 809
7 696
6 584
5 471
4 358
3 245
2 133
1 20

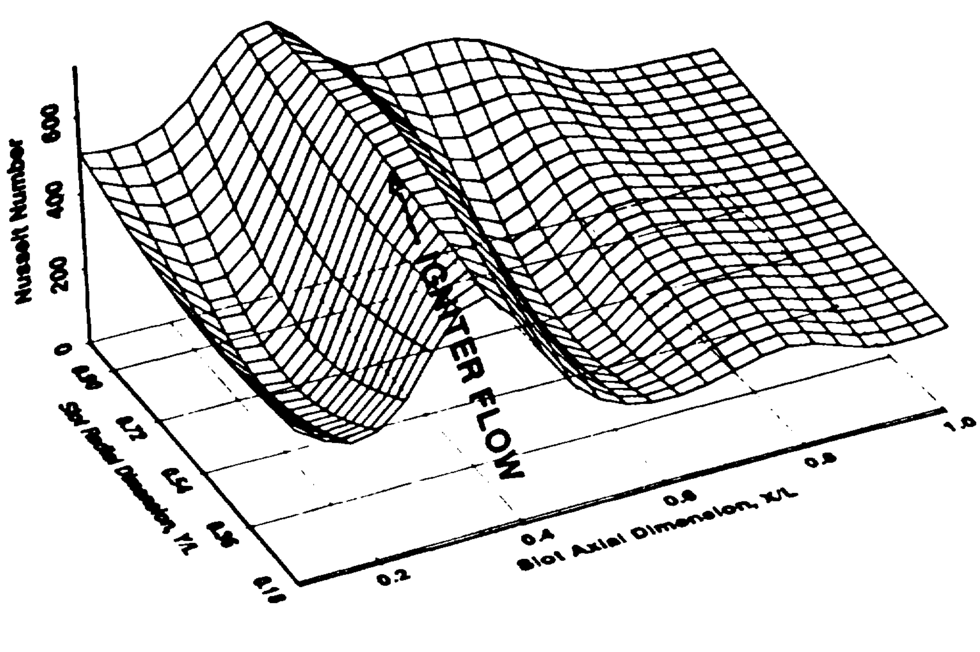
Calculated Heat Transfer, 45° Igniter

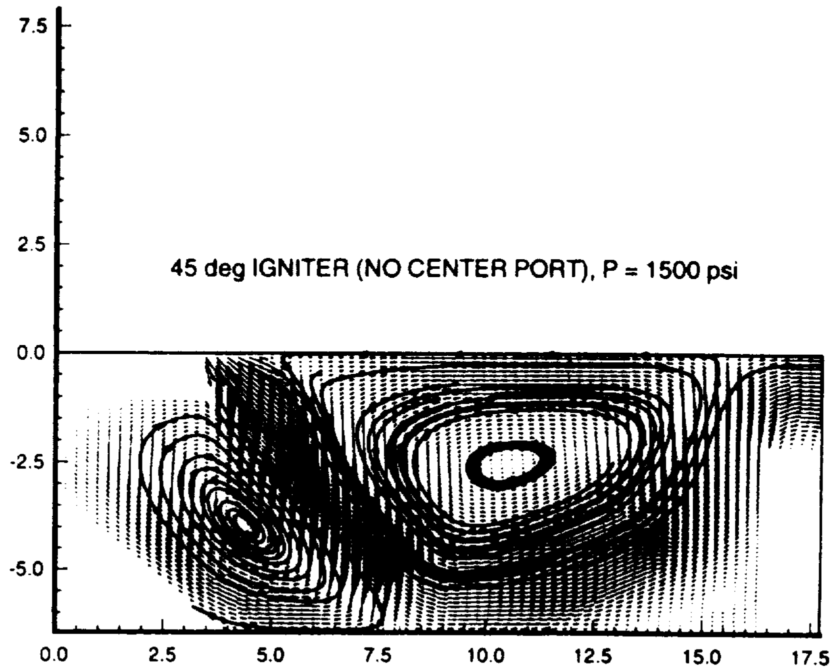
$P_{Igniter}$ = 500 psi

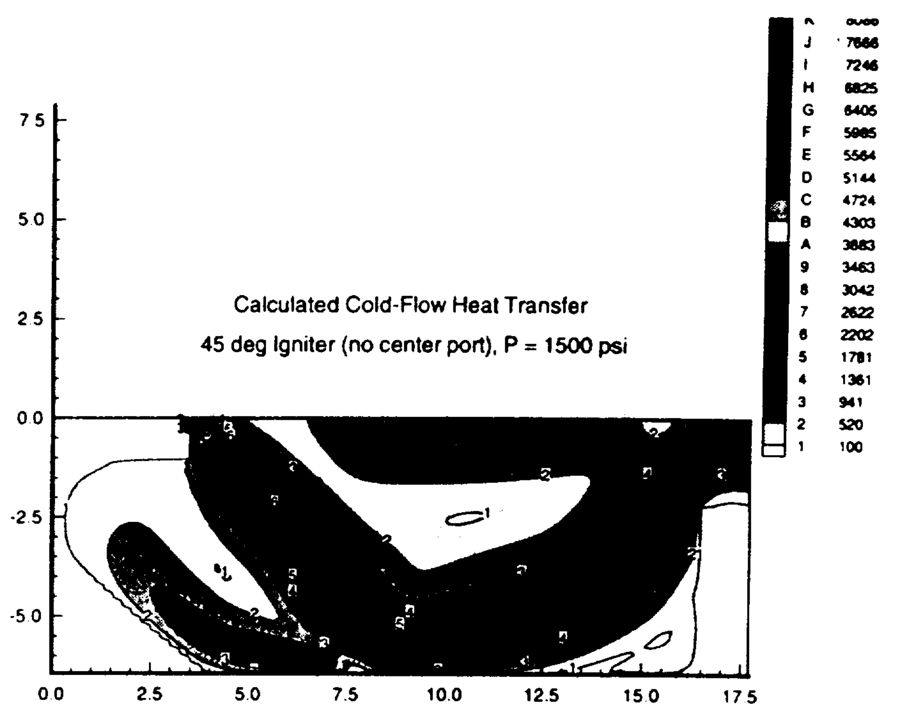


Measured Heat Transfer, 45° Igniter

$P_{Igniter}$ = 500 psi

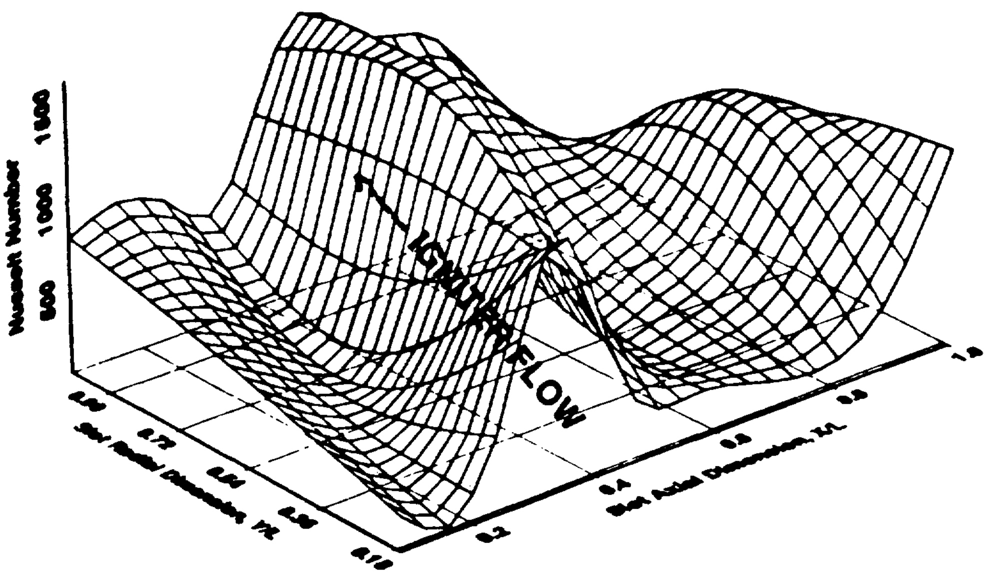



45 deg IGNITER (NO CENTER PORT), P = 1500 psi
7.5
5.0
2.5
0.0
-2.5
-5.0
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5


Calculated Cold-Flow Heat Transfer
45 deg Igniter (no center port), P = 1500 psi
J 7666
I 7246
H 6825
G 6405
F 5985
E 5564
D 5144
C 4724
B 4303
A 3883
9 3463
8 3042
7 2622
6 2202
5 1781
4 1361
3 941
2 520
1 100

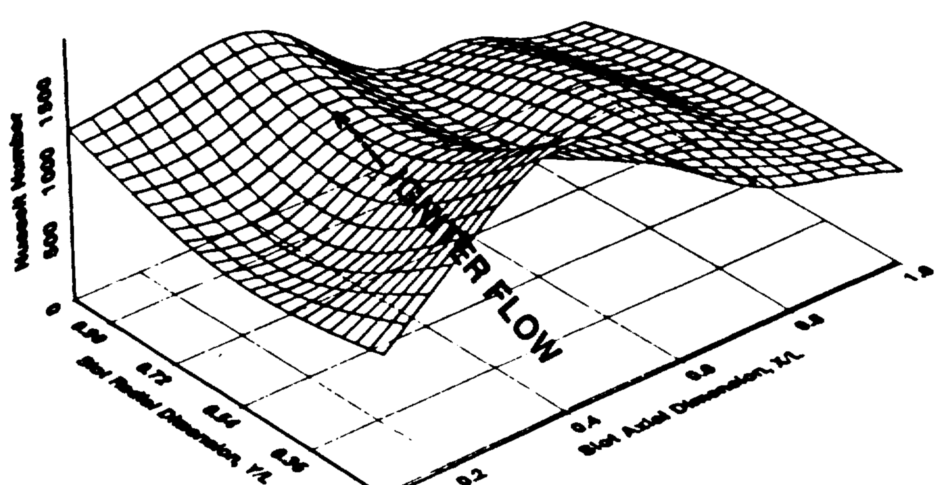
Calculated Heat Transfer, 45° Igniter

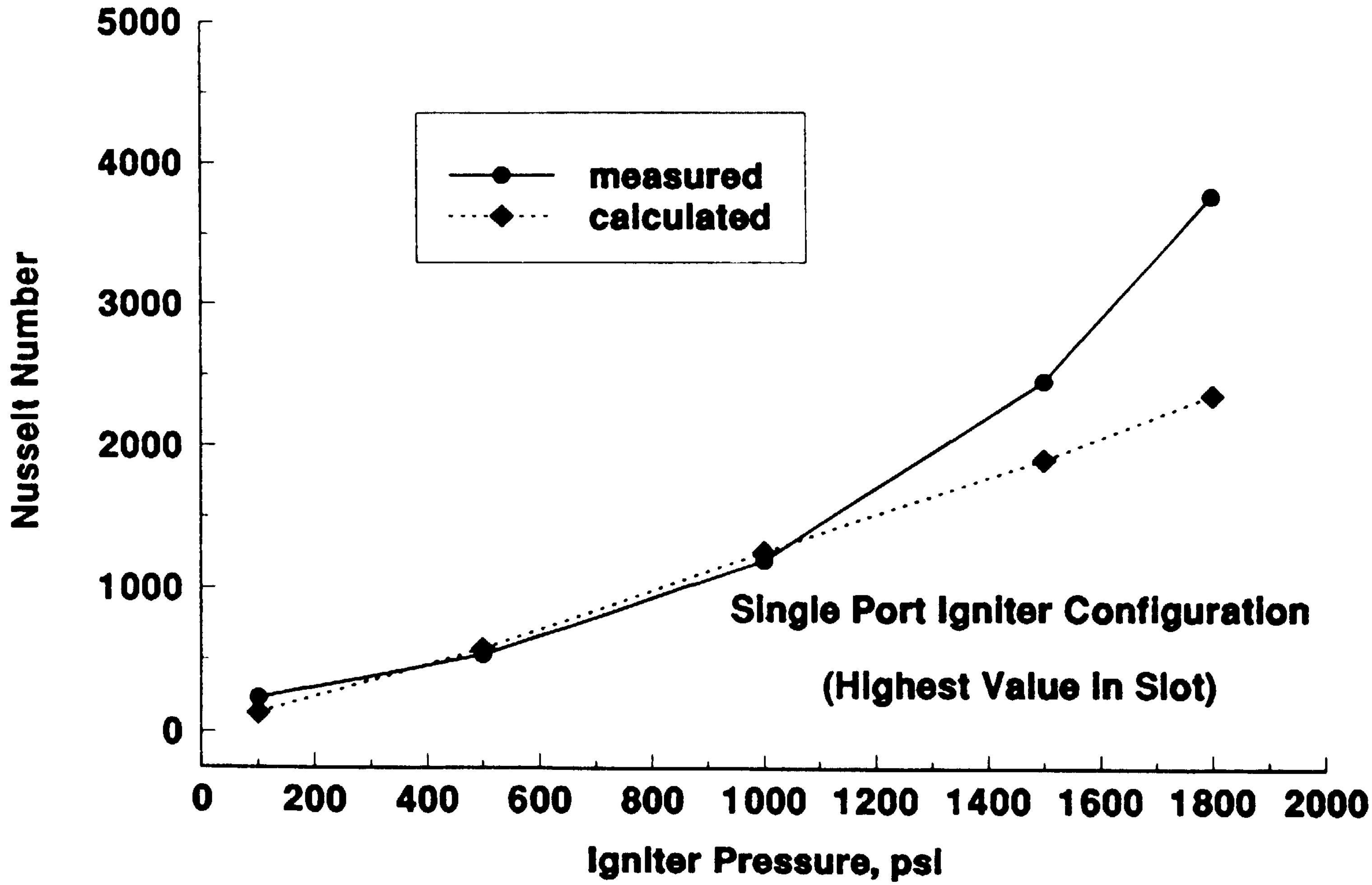
$P_{Igniter}$ = 1500 psi

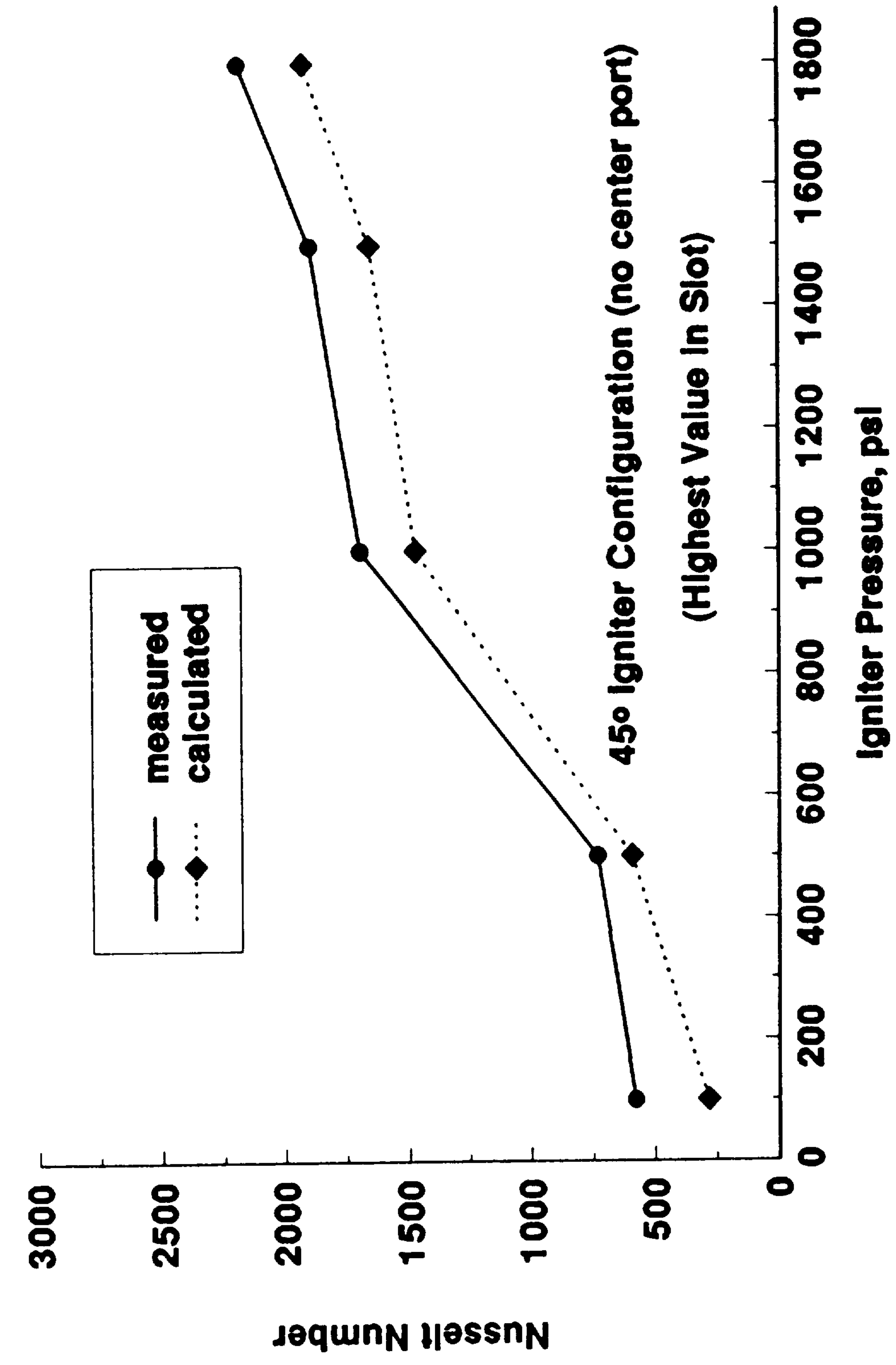


Measured Heat Transfer, 45° Igniter

$P_{Igniter}$ = 1500 psi

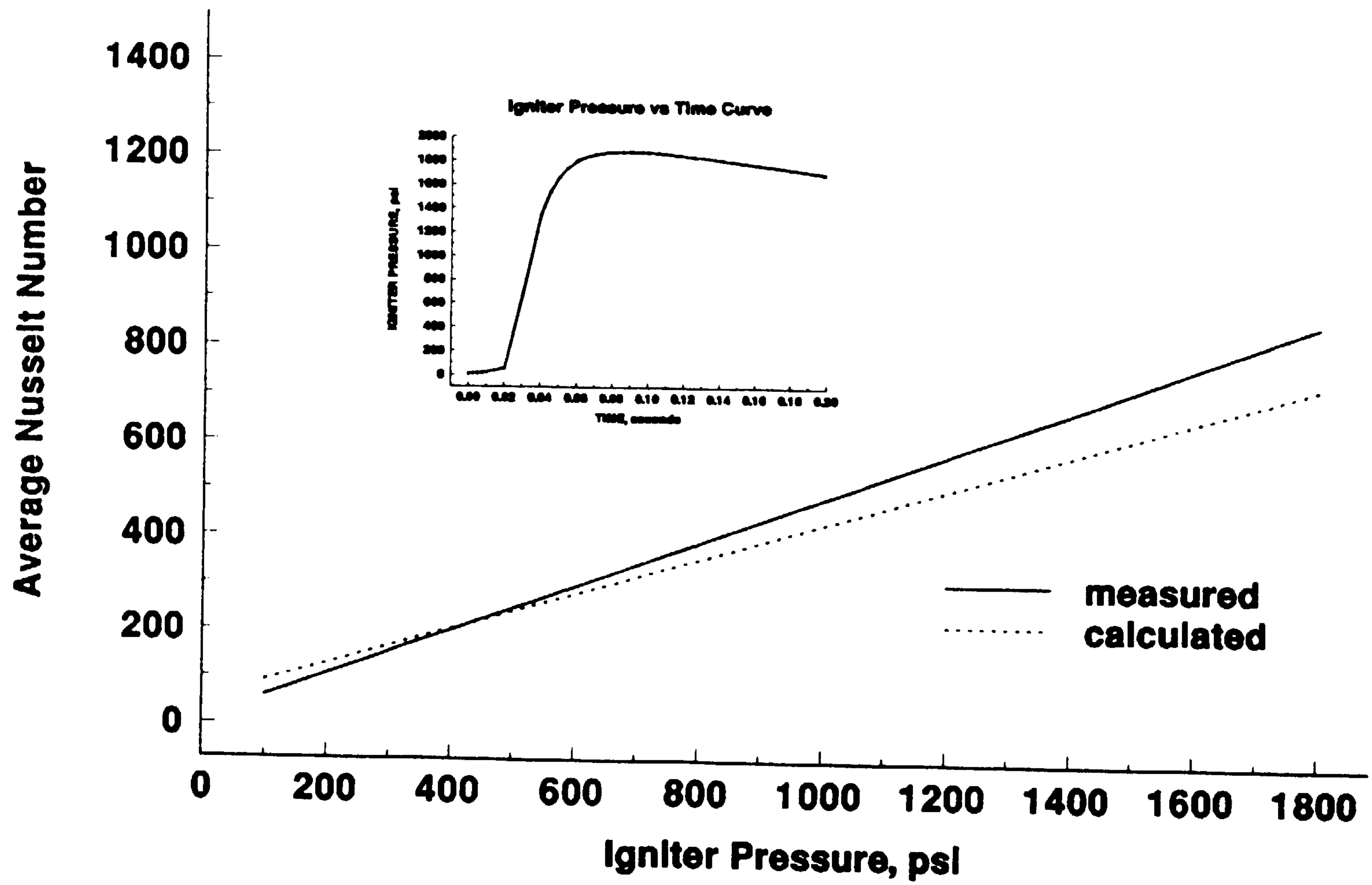


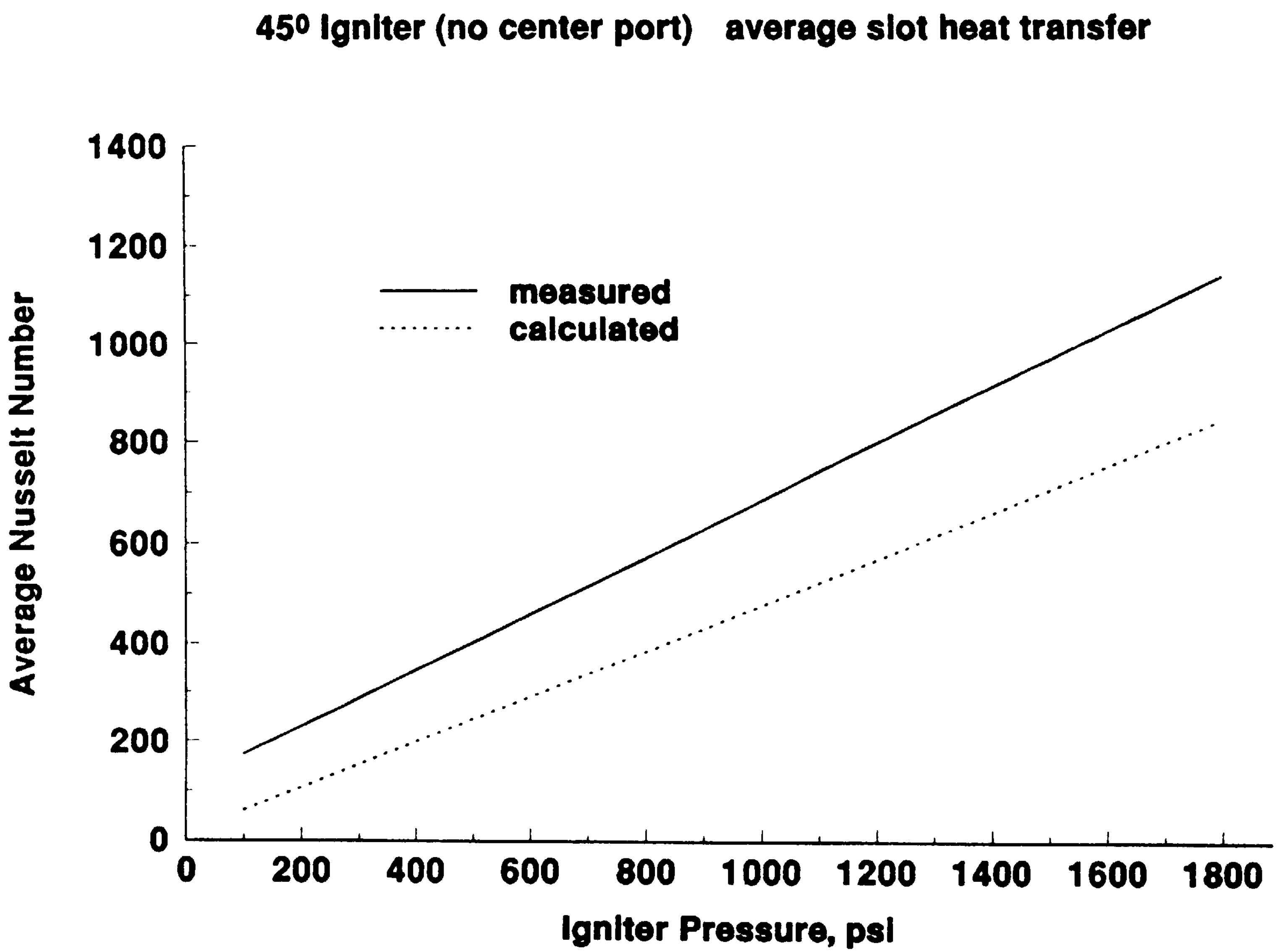

Nusselt Number
5000
4000
3000
2000
1000
0
measured
calculated
Single Port Igniter Configuration
(Highest Value In Slot)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Igniter Pressure, psi

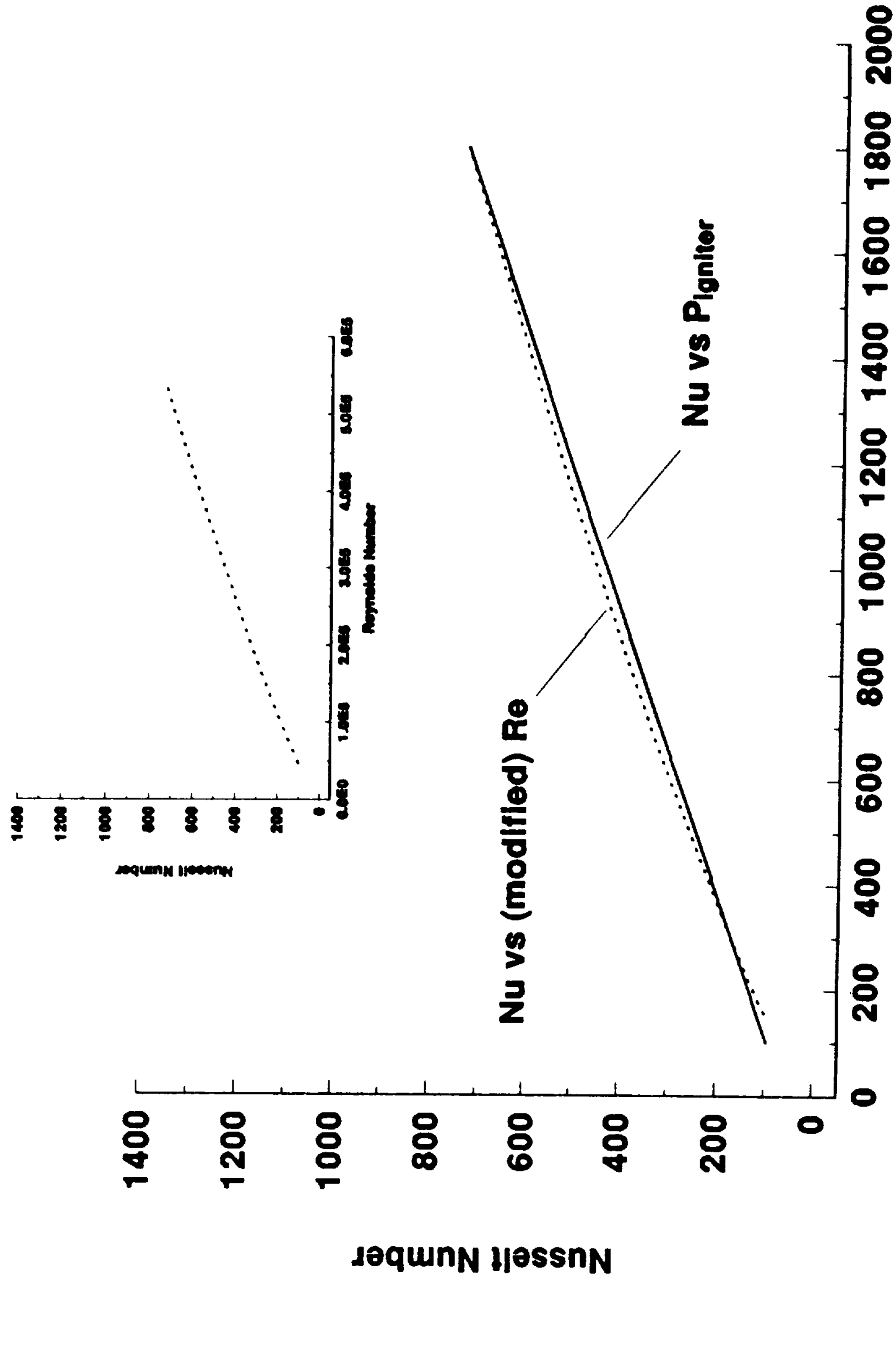


measured
calculated
45° Igniter Configuration (no center port)
(Highest Value in Slot)
Igniter Pressure, psi
Nusselt Number
0
200
400
600
800
1000
1200
1400
1600
1800
500
1000
1500
2000
2500
3000

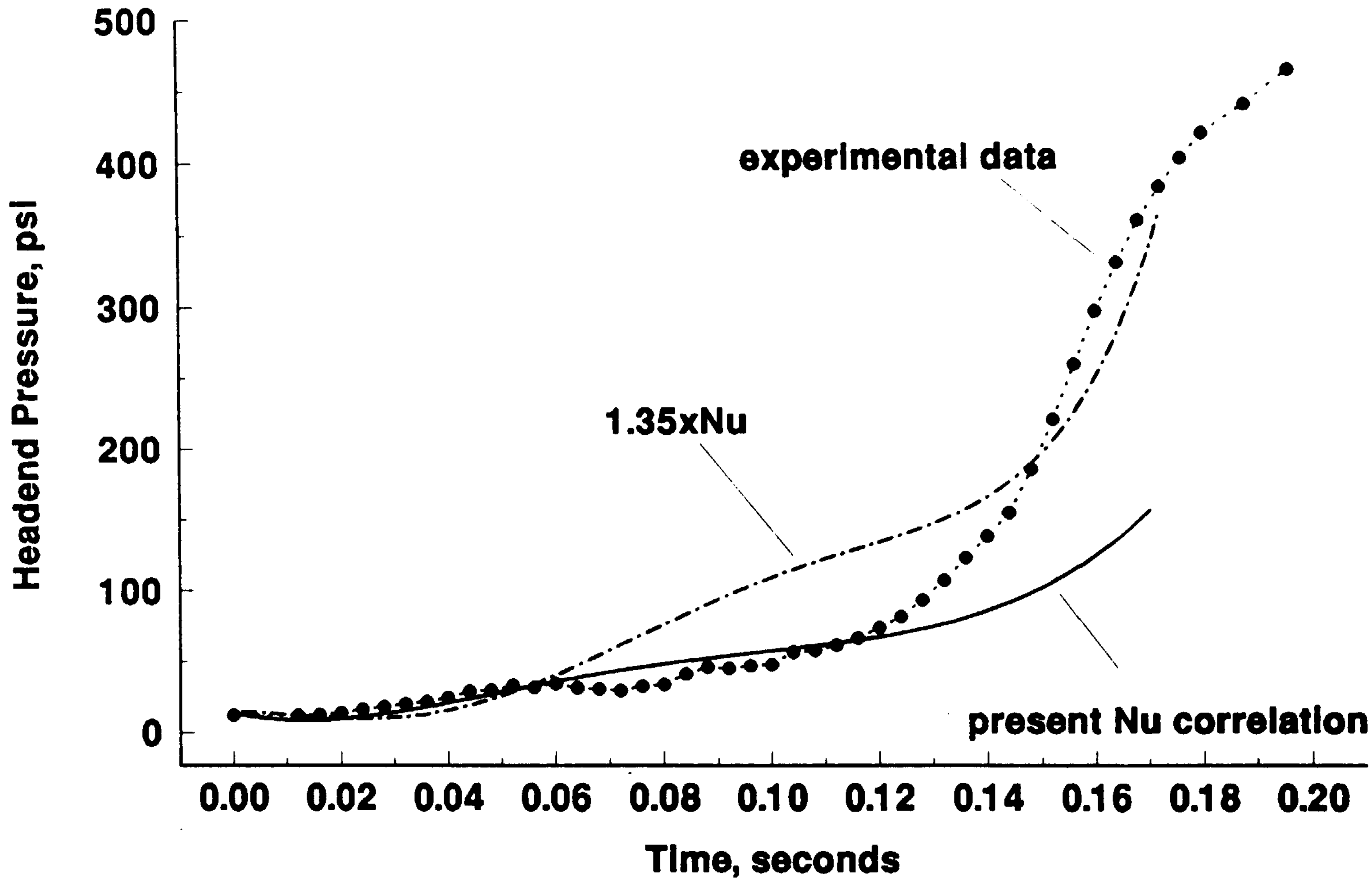
single port igniter (average) slot heat transfer

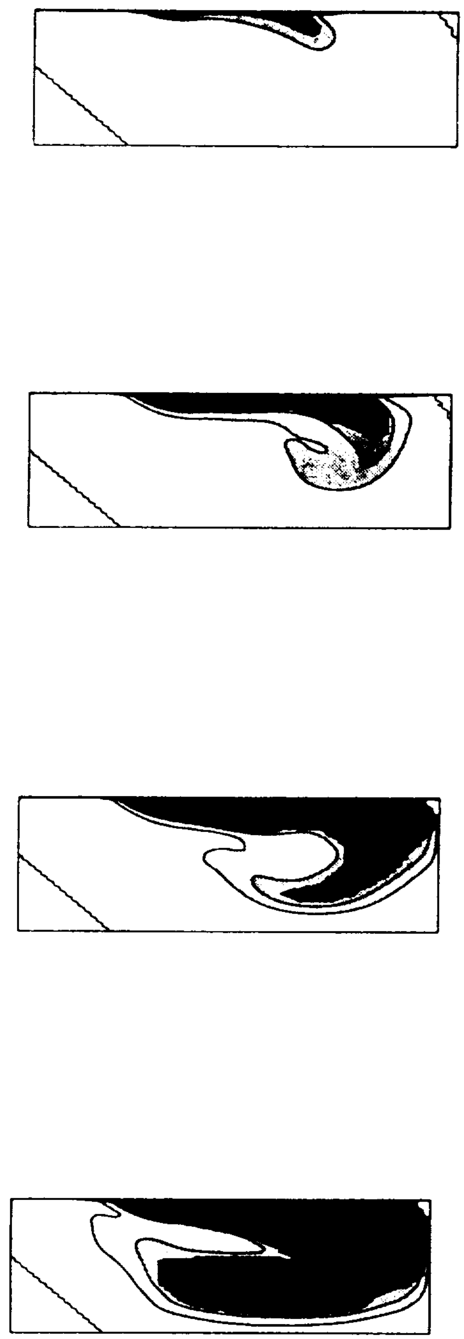



45⁰ Igniter (no center port) average slot heat transfer
Average Nusselt Number
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
Igniter Pressure, psi
measured
calculated


Nusselt Number
1400
1200
1000
800
600
400
200
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Nu vs (modified) Re
Nu vs $P_{Igniter}$
Nusselt Number
Reynolds Number

Sensitivity of Initial Shuttle Head-End Pressure to Assumed Heat Transfer Correlation





TYPICAL FLAME SPREAD CHARACTERISTICS: SINGLE PORT IGNITER

Conclusions: Work-to-Date

- Correlation between the convection heat transfer model utilized and the measured (cold flow) values of heat transfer is generally good.

- For the single port igniter, the heat transfer model utilized increasingly under-predicts the heat transfer as igniter pressure increases.

- For the 45° igniter with no center port, the heat transfer model under-predicts the heat transfer for all igniter pressures, with increasing under-prediction as igniter pressure increases.

- There appears to be a direct correlation between igniter pressure and an average Reynolds number in the star grain slot. This may lead to a simple method for modifying the convection heat transfer correlation.

- Calculated results of pressure-vs-time for the first 200 msec of motor firing of the Space Shuttle SRM tend to support the idea that heat transfer is under-predicted for higher igniter pressures.