

CFD BEST PRACTICES

UNDERSTANDING CFD BEST PRACTICES FOR OPTIMIZED SIMULATIONS

CFD BEST PRACTICES ARE CRUCIAL FOR ANYONE LOOKING TO LEVERAGE COMPUTATIONAL FLUID DYNAMICS EFFECTIVELY AND RELIABLY. ACCURATE AND EFFICIENT SIMULATIONS ARE NOT JUST ABOUT HAVING POWERFUL SOFTWARE; THEY RELY HEAVILY ON A DEEP UNDERSTANDING OF THE UNDERLYING PRINCIPLES AND METICULOUS ATTENTION TO DETAIL THROUGHOUT THE ENTIRE WORKFLOW. THIS ARTICLE DELVES INTO THE ESSENTIAL STRATEGIES AND METHODOLOGIES THAT DEFINE OPTIMAL CFD PRACTICES, COVERING EVERYTHING FROM PROBLEM DEFINITION AND MESHING TO SOLVER SETTINGS, POST-PROCESSING, AND VALIDATION. BY ADHERING TO THESE GUIDELINES, ENGINEERS AND RESEARCHERS CAN SIGNIFICANTLY ENHANCE THE QUALITY OF THEIR SIMULATION RESULTS, REDUCE COMPUTATIONAL COSTS, AND GAIN DEEPER INSIGHTS INTO COMPLEX FLUID FLOW PHENOMENA. WE WILL EXPLORE HOW TO SET UP YOUR SIMULATIONS FOR SUCCESS, ENSURING THAT YOUR CFD MODELS ACCURATELY REPRESENT THE PHYSICAL REALITY THEY AIM TO EMULATE, LEADING TO MORE INFORMED DESIGN DECISIONS AND INNOVATIVE SOLUTIONS.

- DEFINING THE PROBLEM SCOPE AND OBJECTIVES
- GEOMETRY PREPARATION AND SIMPLIFICATION
- MESHING STRATEGIES AND QUALITY CONTROL
- SOLVER SELECTION AND SETUP
- BOUNDARY CONDITIONS AND INITIALIZATION
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- CONVERGENCE CRITERIA AND MONITORING
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- ADVANCED CFD BEST PRACTICES

DEFINING THE PROBLEM SCOPE AND OBJECTIVES

THE FIRST AND PERHAPS MOST CRITICAL STEP IN ANY CFD ANALYSIS IS TO CLEARLY DEFINE THE PROBLEM SCOPE AND THE SPECIFIC OBJECTIVES OF THE SIMULATION. WITHOUT A WELL-DEFINED PURPOSE, SIMULATIONS CAN BECOME UNFOCUSED, LEADING TO WASTED COMPUTATIONAL RESOURCES AND INCONCLUSIVE RESULTS. THIS STAGE INVOLVES UNDERSTANDING WHAT QUESTIONS NEED TO BE ANSWERED, WHAT PARAMETERS ARE OF INTEREST, AND THE LEVEL OF ACCURACY REQUIRED FOR THE INTENDED APPLICATION. A CLEAR OBJECTIVE WILL GUIDE EVERY SUBSEQUENT DECISION, FROM GEOMETRY SIMPLIFICATION TO THE CHOICE OF NUMERICAL MODELS AND ANALYSIS TECHNIQUES.

IT IS ESSENTIAL TO DOCUMENT THESE OBJECTIVES THOROUGHLY. THIS DOCUMENTATION SERVES AS A REFERENCE POINT THROUGHOUT THE PROJECT AND HELPS ENSURE THAT ALL TEAM MEMBERS ARE ALIGNED. CONSIDER THE PHYSICAL PHENOMENA THAT ARE DOMINANT AND THOSE THAT CAN BE REASONABLY NEGLECTED. FOR INSTANCE, IS THE FLOW LAMINAR OR TURBULENT? IS HEAT TRANSFER SIGNIFICANT? ARE COMPRESSIBLE EFFECTS IMPORTANT, OR CAN THE FLUID BE TREATED AS INCOMPRESSIBLE? ANSWERING THESE FUNDAMENTAL QUESTIONS WILL DICTATE THE COMPLEXITY OF THE CFD MODEL REQUIRED.

GEOMETRY PREPARATION AND SIMPLIFICATION

THE QUALITY OF THE SIMULATION RESULTS IS DIRECTLY INFLUENCED BY THE QUALITY OF THE GEOMETRY USED. PREPARATION OFTEN INVOLVES CLEANING UP IMPORTED CAD MODELS, REMOVING UNNECESSARY FEATURES THAT DO NOT IMPACT THE FLOW FIELD, AND ENSURING THE GEOMETRY IS WATERTIGHT. SMALL GAPS, OVERLAPPING SURFACES, OR SLIVER SURFACES CAN LEAD TO MESHING DIFFICULTIES AND NUMERICAL INSTABILITIES.

SIMPLIFICATION IS A KEY ASPECT OF GEOMETRY PREPARATION IN CFD BEST PRACTICES. COMPLEX CAD MODELS OFTEN CONTAIN INTRICATE DETAILS THAT ARE COMPUTATIONALLY EXPENSIVE TO MESH AND SIMULATE WITHOUT SIGNIFICANTLY ADDING TO THE ACCURACY OF THE RESULTS. IDENTIFYING AND REMOVING THESE IRRELEVANT FEATURES CAN DRASTICALLY REDUCE MESHING TIME AND COMPUTATIONAL LOAD. FOR EXAMPLE, SMALL FILLETS, CHAMFERS, OR BOLT HOLES THAT DO NOT INFLUENCE THE PRIMARY FLOW PATTERNS CAN OFTEN BE SUPPRESSED OR REPLACED WITH SIMPLIFIED REPRESENTATIONS. THE GOAL IS TO CREATE A GEOMETRY THAT ACCURATELY REPRESENTS THE ESSENTIAL PHYSICS WHILE REMAINING COMPUTATIONALLY MANAGEABLE.

MESHING STRATEGIES AND QUALITY CONTROL

THE MESH IS THE DISCRETE REPRESENTATION OF THE COMPUTATIONAL DOMAIN, AND ITS QUALITY IS PARAMOUNT FOR ACCURATE CFD SIMULATIONS. A GOOD MESH SHOULD RESOLVE THE RELEVANT FLOW FEATURES, SUCH AS BOUNDARY LAYERS, SHEAR LAYERS, AND RECIRCULATION ZONES, WHILE REMAINING AS COARSE AS POSSIBLE IN REGIONS OF UNIFORM FLOW TO SAVE COMPUTATIONAL RESOURCES. THE CHOICE OF MESHING STRATEGY – WHETHER STRUCTURED, UNSTRUCTURED, OR HYBRID – DEPENDS ON THE GEOMETRY AND THE FLOW CHARACTERISTICS.

KEY ASPECTS OF MESHING QUALITY INCLUDE:

- **ELEMENT ASPECT RATIO:** THE RATIO OF THE LONGEST TO SHORTEST EDGE OF AN ELEMENT. HIGH ASPECT RATIOS CAN LEAD TO NUMERICAL ERRORS.
- **SKEWNESS:** A MEASURE OF HOW MUCH AN ELEMENT DEVIATES FROM BEING ORTHOGONAL. HIGH SKEWNESS CAN DESTABILIZE THE SOLUTION.
- **ORTHOGONALITY:** THE DEGREE TO WHICH CELL FACES ARE PERPENDICULAR TO THE CELL CENTERS. HIGHER ORTHOGONALITY IS GENERALLY PREFERRED.
- **SMOOTHNESS:** THE RATE OF CHANGE IN CELL SIZE BETWEEN ADJACENT CELLS. ABRUPT CHANGES CAN CAUSE NUMERICAL DIFFUSION.

REGULAR MESH QUALITY CHECKS ARE ESSENTIAL. MOST CFD SOFTWARE PROVIDES TOOLS TO VISUALIZE AND QUANTIFY MESH QUALITY METRICS. ADDRESSING POOR QUALITY CELLS BEFORE RUNNING THE SIMULATION CAN PREVENT CONVERGENCE ISSUES AND SAVE CONSIDERABLE TIME.

SOLVER SELECTION AND SETUP

CHOOSING THE APPROPRIATE SOLVER AND CONFIGURING ITS SETTINGS CORRECTLY ARE VITAL FOR OBTAINING ACCURATE AND STABLE CFD RESULTS. THE SOLVER ALGORITHM, DISCRETIZATION SCHEMES, AND NUMERICAL PRECISION ALL PLAY A SIGNIFICANT ROLE. FOR INSTANCE, THE CHOICE BETWEEN PRESSURE-BASED AND DENSITY-BASED SOLVERS DEPENDS ON THE FLOW REGIME (E.G., INCOMPRESSIBLE VS. COMPRESSIBLE FLOWS).

THE DISCRETIZATION SCHEMES USED TO APPROXIMATE THE GOVERNING EQUATIONS (E.G., NAVIER-STOKES) ON THE MESH ARE CRITICAL. FIRST-ORDER SCHEMES ARE GENERALLY MORE STABLE BUT LESS ACCURATE, WHILE SECOND-ORDER OR HIGHER-ORDER

SCHEMES OFFER BETTER ACCURACY BUT CAN BE MORE PRONE TO INSTABILITY, ESPECIALLY WITH POOR QUALITY MESHES OR STRONG GRADIENTS. A COMMON PRACTICE IS TO START WITH A SECOND-ORDER SCHEME FOR ACCURACY, BUT IN SOME CASES, A FIRST-ORDER SCHEME MIGHT BE NECESSARY FOR INITIAL CONVERGENCE, FOLLOWED BY A SWITCH TO A HIGHER-ORDER SCHEME.

BOUNDARY CONDITIONS AND INITIALIZATION

BOUNDARY CONDITIONS DEFINE THE INTERACTION OF THE FLUID WITH ITS SURROUNDINGS AND ARE FUNDAMENTAL TO A CORRECT CFD SIMULATION. INACCURATE OR IMPROPERLY APPLIED BOUNDARY CONDITIONS ARE A COMMON SOURCE OF ERROR. IT IS CRUCIAL TO SELECT BOUNDARY CONDITIONS THAT ACCURATELY REPRESENT THE PHYSICAL SITUATION BEING MODELED. THIS INCLUDES SPECIFYING INFLOW VELOCITIES, PRESSURES, MASS FLOW RATES, WALL CONDITIONS (E.G., NO-SLIP, SLIP, TEMPERATURE), AND OUTFLOW CONDITIONS.

INITIALIZATION OF THE FLOW FIELD ALSO PLAYS A ROLE IN ACHIEVING CONVERGENCE, ESPECIALLY FOR COMPLEX OR TURBULENT FLOWS. A GOOD INITIAL GUESS CAN REDUCE THE NUMBER OF ITERATIONS REQUIRED AND HELP THE SOLVER AVOID SPURIOUS OSCILLATIONS. OFTEN, INITIALIZING WITH A SIMPLE UNIFORM FLOW FIELD AT A REPRESENTATIVE VELOCITY IS SUFFICIENT. HOWEVER, FOR CERTAIN PROBLEMS, A MORE SOPHISTICATED INITIALIZATION BASED ON PRIOR SIMULATIONS OR EMPIRICAL DATA MIGHT BE BENEFICIAL.

TURBULENCE MODELING CONSIDERATIONS

TURBULENCE IS A UBIQUITOUS PHENOMENON IN FLUID MECHANICS AND PRESENTS A SIGNIFICANT CHALLENGE FOR CFD DUE TO ITS CHAOTIC AND MULTI-SCALE NATURE. DIRECT NUMERICAL SIMULATION (DNS) IS THE MOST ACCURATE METHOD BUT IS COMPUTATIONALLY PROHIBITIVE FOR MOST ENGINEERING APPLICATIONS. THEREFORE, TURBULENCE MODELS ARE EMPLOYED TO APPROXIMATE THE EFFECTS OF TURBULENCE.

COMMON TURBULENCE MODELING APPROACHES INCLUDE:

- **REYNOLDS-AVERAGED NAVIER-STOKES (RANS):** MODELS LIKE K-EPSILON AND K-OMEGA ARE WIDELY USED FOR THEIR COMPUTATIONAL EFFICIENCY, BUT THEY PROVIDE TIME-AVERAGED INFORMATION AND MAY NOT ACCURATELY CAPTURE TRANSIENT TURBULENT PHENOMENA.
- **LARGE EDDY SIMULATION (LES):** RESOLVES LARGE TURBULENT EDDIES DIRECTLY AND MODELS THE SMALLER, SUB-GRID SCALE EDDIES. LES IS MORE ACCURATE THAN RANS FOR TIME-DEPENDENT FLOWS BUT IS COMPUTATIONALLY MORE EXPENSIVE.
- **DETACHED EDDY SIMULATION (DES):** A HYBRID APPROACH THAT USES LES IN REGIONS WHERE RESOLVED EDDIES ARE IMPORTANT AND RANS IN REGIONS WHERE THE FLOW IS MORE STEADY OR COMPUTATIONALLY EXPENSIVE TO RESOLVE.

THE CHOICE OF TURBULENCE MODEL DEPENDS ON THE FLOW PHYSICS, THE DESIRED LEVEL OF ACCURACY, AND THE AVAILABLE COMPUTATIONAL RESOURCES. IT IS IMPORTANT TO SELECT A MODEL APPROPRIATE FOR THE SPECIFIC FLOW REGIME AND TO VALIDATE ITS PERFORMANCE AGAINST EXPERIMENTAL DATA OR ESTABLISHED CORRELATIONS.

CONVERGENCE CRITERIA AND MONITORING

CONVERGENCE IS THE STATE WHERE THE NUMERICAL SOLUTION HAS REACHED A STEADY OR STATISTICALLY STEADY STATE, MEANING THAT THE GOVERNING EQUATIONS ARE SATISFIED WITHIN ACCEPTABLE TOLERANCES. ESTABLISHING APPROPRIATE CONVERGENCE CRITERIA IS VITAL TO ENSURE THE RELIABILITY OF THE SIMULATION RESULTS.

KEY INDICATORS FOR MONITORING CONVERGENCE INCLUDE:

- **RESIDUALS:** THESE REPRESENT THE IMBALANCE IN THE DISCRETIZED GOVERNING EQUATIONS AT EACH ITERATION. THE RESIDUALS SHOULD DECREASE BY SEVERAL ORDERS OF MAGNITUDE (TYPICALLY TO 10^{-4} OR LOWER, DEPENDING ON THE PROBLEM) FOR ALL GOVERNING EQUATIONS.
- **MONITORED VARIABLES:** SPECIFIC PHYSICAL QUANTITIES OF INTEREST, SUCH AS LIFT, DRAG, PRESSURE DROP, OR TEMPERATURE AT A PARTICULAR POINT, SHOULD STABILIZE OVER ITERATIONS.
- **MASS CONSERVATION:** FOR STEADY-STATE SIMULATIONS, ENSURING THAT THE NET MASS FLOW RATE ACROSS BOUNDARIES IS ZERO IS A CRUCIAL CHECK.

IT IS IMPORTANT TO DISTINGUISH BETWEEN NUMERICAL CONVERGENCE AND PHYSICAL CONVERGENCE. A SOLUTION MAY BE NUMERICALLY CONVERGED (RESIDUALS ARE LOW) BUT MAY NOT REPRESENT THE TRUE PHYSICAL STEADY STATE IF THE SIMULATION TIME IS INSUFFICIENT OR IF THE PROBLEM INHERENTLY INVOLVES UNSTEADY PHENOMENA THAT WERE NOT INTENDED TO BE CAPTURED IN A STEADY-STATE ANALYSIS.

POST-PROCESSING AND DATA ANALYSIS

ONCE THE SIMULATION HAS CONVERGED, THE NEXT STEP IS TO EXTRACT MEANINGFUL INFORMATION FROM THE VAST AMOUNT OF DATA GENERATED. POST-PROCESSING INVOLVES VISUALIZING THE FLOW FIELD AND CALCULATING KEY PERFORMANCE METRICS. THIS STAGE IS WHERE THE INSIGHTS FROM THE SIMULATION ARE REALIZED.

EFFECTIVE POST-PROCESSING INCLUDES:

- **VISUALIZATION:** CREATING CONTOUR PLOTS, VECTOR PLOTS, STREAMLINES, AND SURFACE PLOTS TO UNDERSTAND THE FLOW PATTERNS, IDENTIFY RECIRCULATION ZONES, SEPARATION POINTS, AND REGIONS OF HIGH GRADIENTS.
- **QUANTITATIVE ANALYSIS:** CALCULATING INTEGRATED QUANTITIES SUCH AS FORCES (LIFT, DRAG), MOMENTS, FLOW RATES, HEAT TRANSFER COEFFICIENTS, AND PRESSURE DROPS.
- **DATA EXTRACTION:** SAMPLING DATA AT SPECIFIC POINTS OR ALONG LINES TO CREATE PLOTS OF VELOCITY PROFILES, TEMPERATURE DISTRIBUTIONS, OR PRESSURE VARIATIONS.

THE INTERPRETATION OF POST-PROCESSED DATA SHOULD ALWAYS BE DONE IN THE CONTEXT OF THE ORIGINAL PROBLEM OBJECTIVES. UNDERSTANDING THE LIMITATIONS OF THE CFD MODEL AND THE ASSUMPTIONS MADE IS CRUCIAL FOR DRAWING VALID CONCLUSIONS.

VALIDATION AND VERIFICATION OF RESULTS

VALIDATION AND VERIFICATION ARE DISTINCT BUT EQUALLY IMPORTANT PROCESSES FOR ENSURING THE CREDIBILITY OF CFD RESULTS. VERIFICATION ASSESSES WHETHER THE NUMERICAL SOLUTION CORRECTLY SOLVES THE MATHEMATICAL MODEL. THIS INVOLVES TASKS LIKE MESH INDEPENDENCE STUDIES (ENSURING THE SOLUTION IS NOT OVERLY SENSITIVE TO THE MESH RESOLUTION) AND CHECKING FOR CONSERVATION LAWS.

VALIDATION, ON THE OTHER HAND, ASSESSES WHETHER THE MATHEMATICAL MODEL ACCURATELY REPRESENTS THE PHYSICAL REALITY. THIS IS ACHIEVED BY COMPARING CFD SIMULATION RESULTS AGAINST EXPERIMENTAL DATA, ANALYTICAL SOLUTIONS, OR RESULTS FROM WELL-ESTABLISHED EMPIRICAL CORRELATIONS. DISCREPANCIES BETWEEN SIMULATION AND VALIDATION DATA

SHOULD BE INVESTIGATED TO UNDERSTAND THEIR ROOT CAUSE. THIS MIGHT INVOLVE REFINING THE MESH, ADJUSTING TURBULENCE MODELS, IMPROVING BOUNDARY CONDITIONS, OR EVEN QUESTIONING THE APPLICABILITY OF THE CHOSEN MATHEMATICAL MODEL.

ADVANCED CFD BEST PRACTICES

BEYOND THE FUNDAMENTAL PRACTICES, SEVERAL ADVANCED TECHNIQUES CAN FURTHER ENHANCE THE RELIABILITY AND EFFICIENCY OF CFD SIMULATIONS. THESE INCLUDE THE USE OF ADAPTIVE MESHING, WHICH REFINES THE MESH AUTOMATICALLY IN REGIONS OF HIGH GRADIENTS OR ERRORS, THEREBY IMPROVING ACCURACY WITH FEWER COMPUTATIONAL RESOURCES. EMPLOYING ADVANCED INITIALIZATION TECHNIQUES, SUCH AS USING RESULTS FROM A COARSER MESH OR A SIMPLER MODEL AS A STARTING POINT, CAN ACCELERATE CONVERGENCE FOR COMPLEX SIMULATIONS.

FURTHERMORE, UNCERTAINTY QUANTIFICATION (UQ) IS BECOMING INCREASINGLY IMPORTANT. UQ METHODS AIM TO SYSTEMATICALLY IDENTIFY, CHARACTERIZE, AND PROPAGATE UNCERTAINTIES IN INPUT PARAMETERS (E.G., BOUNDARY CONDITIONS, MATERIAL PROPERTIES) THROUGH THE CFD MODEL TO QUANTIFY THE UNCERTAINTY IN THE SIMULATION OUTPUTS. THIS PROVIDES A MORE REALISTIC ASSESSMENT OF THE RELIABILITY OF THE PREDICTIONS AND HELPS IN MAKING MORE ROBUST DESIGN DECISIONS.

FAQ

Q: WHAT IS THE MOST CRITICAL STEP IN CFD BEST PRACTICES?

A: THE MOST CRITICAL STEP IN CFD BEST PRACTICES IS CLEARLY DEFINING THE PROBLEM SCOPE AND OBJECTIVES. WITHOUT A WELL-DEFINED PURPOSE, SIMULATIONS CAN BECOME UNFOCUSED, LEADING TO WASTED RESOURCES AND INCONCLUSIVE RESULTS, IMPACTING ALL SUBSEQUENT STAGES OF THE CFD WORKFLOW.

Q: HOW DOES GEOMETRY SIMPLIFICATION IMPACT CFD SIMULATIONS?

A: GEOMETRY SIMPLIFICATION IS CRUCIAL FOR CFD BEST PRACTICES AS IT REDUCES COMPUTATIONAL COMPLEXITY, DECREASES MESHING TIME, AND LOWERS THE RISK OF NUMERICAL INSTABILITIES. IT INVOLVES REMOVING FINE DETAILS THAT DO NOT SIGNIFICANTLY AFFECT THE PRIMARY FLOW PHYSICS, MAKING THE SIMULATION MORE EFFICIENT AND MANAGEABLE WITHOUT SACRIFICING ESSENTIAL ACCURACY.

Q: WHAT ARE THE KEY METRICS FOR ASSESSING MESH QUALITY IN CFD?

A: KEY METRICS FOR ASSESSING MESH QUALITY IN CFD INCLUDE ELEMENT ASPECT RATIO, SKEWNESS, ORTHOGONALITY, AND SMOOTHNESS. POOR VALUES IN THESE METRICS CAN LEAD TO NUMERICAL ERRORS, CONVERGENCE ISSUES, AND REDUCED ACCURACY OF THE SIMULATION RESULTS.

Q: WHEN SHOULD A FIRST-ORDER DISCRETIZATION SCHEME BE PREFERRED OVER A SECOND-ORDER SCHEME IN CFD?

A: A FIRST-ORDER DISCRETIZATION SCHEME SHOULD BE PREFERRED WHEN FACING CONVERGENCE DIFFICULTIES WITH HIGHER-ORDER SCHEMES, ESPECIALLY WITH POOR QUALITY MESHES OR STRONG FLOW GRADIENTS. WHILE LESS ACCURATE, IT OFFERS GREATER NUMERICAL STABILITY, OFTEN SERVING AS A STARTING POINT BEFORE SWITCHING TO A MORE ACCURATE SECOND-ORDER SCHEME.

Q: HOW CAN THE ACCURACY OF CFD RESULTS BE VALIDATED?

A: THE ACCURACY OF CFD RESULTS IS VALIDATED BY COMPARING THEM AGAINST EXPERIMENTAL DATA, ANALYTICAL SOLUTIONS, OR ESTABLISHED EMPIRICAL CORRELATIONS. THIS PROCESS HELPS TO ENSURE THAT THE MATHEMATICAL MODEL

USED IN THE CFD SIMULATION ACCURATELY REPRESENTS THE REAL-WORLD PHYSICAL PHENOMENA BEING STUDIED.

Q: WHAT IS THE DIFFERENCE BETWEEN VERIFICATION AND VALIDATION IN CFD?

A: VERIFICATION IN CFD CONFIRMS THAT THE NUMERICAL SOLUTION CORRECTLY SOLVES THE MATHEMATICAL MODEL, OFTEN INVOLVING MESH INDEPENDENCE STUDIES AND CHECKING CONSERVATION LAWS. VALIDATION, ON THE OTHER HAND, ASSESSES WHETHER THE MATHEMATICAL MODEL ACCURATELY REPRESENTS THE PHYSICAL REALITY BY COMPARING SIMULATION RESULTS WITH EXPERIMENTAL DATA.

Q: WHY IS TURBULENCE MODELING IMPORTANT IN CFD?

A: TURBULENCE MODELING IS IMPORTANT IN CFD BECAUSE ACCURATELY RESOLVING THE COMPLEX, MULTI-SCALE NATURE OF TURBULENT FLOWS DIRECTLY IS COMPUTATIONALLY INFEASIBLE FOR MOST ENGINEERING APPLICATIONS. TURBULENCE MODELS APPROXIMATE THE EFFECTS OF TURBULENCE, ALLOWING FOR PRACTICAL SIMULATIONS OF TURBULENT FLOWS.

Q: WHAT ARE THE BENEFITS OF USING ADAPTIVE MESHING IN CFD?

A: ADAPTIVE MESHING IN CFD OFFERS THE BENEFIT OF AUTOMATICALLY REFINING THE MESH IN REGIONS WHERE HIGH GRADIENTS OR ERRORS ARE DETECTED. THIS LEADS TO IMPROVED ACCURACY AND EFFICIENCY BY CONCENTRATING COMPUTATIONAL EFFORT ONLY WHERE IT IS MOST NEEDED, OFTEN WITH FEWER CELLS THAN A UNIFORMLY REFINED MESH.

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