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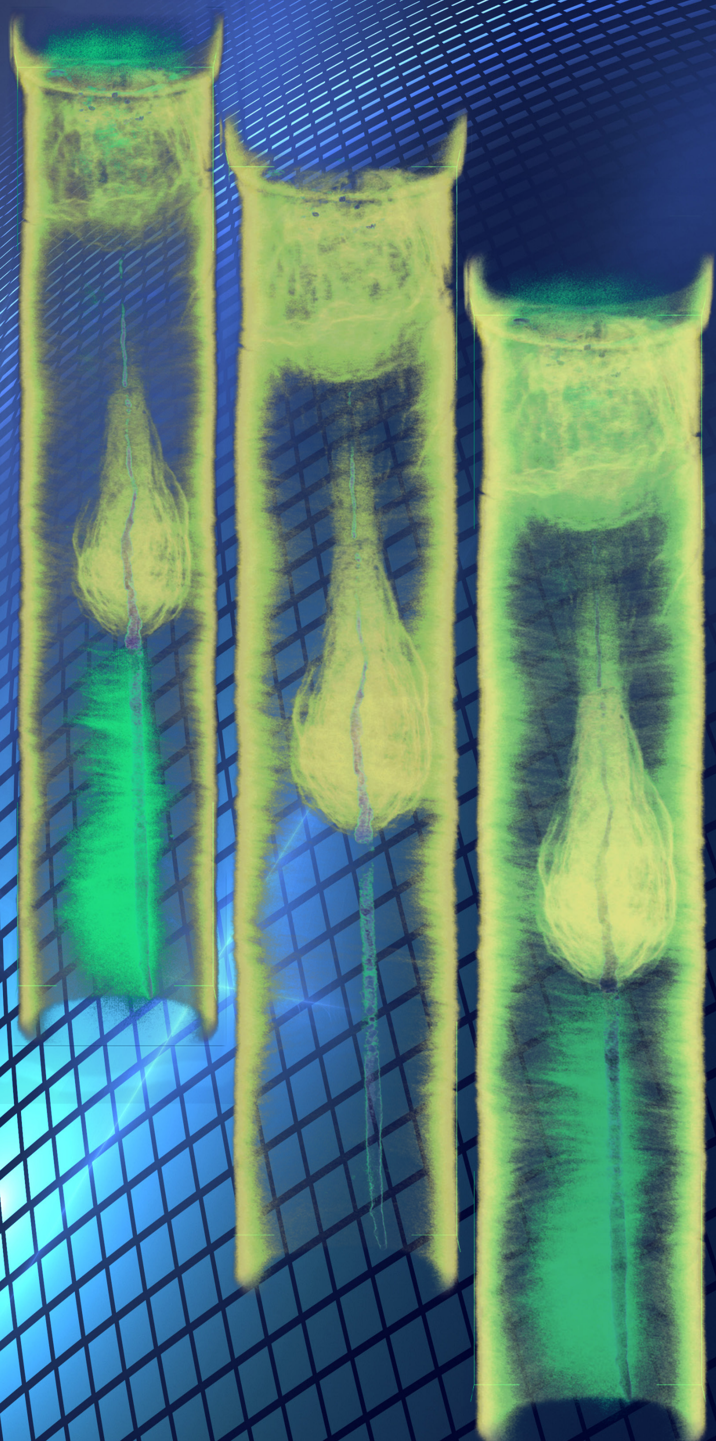
JOURNAL OF THE IPF

A Journal For The International Perforating Industry



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INSIDE

MESSAGE FROM THE IPF BOARD OF DIRECTORS

James Barker

Mark Brinsden

John JW Segura

2016 was a busy year for the International Perforating Forum (IPFC) and the multitude of volunteers who donate their time, efforts, and sponsorship funds to the perforating symposia and forums around the world. The three regional symposia included participation from over 30 sponsors in North America, South America, and the Middle East/North Africa. A big thank you to all in bringing together industry leaders to share ongoing advancements in perforating effectiveness, efficiency, and safety!!! In addition to the regional symposia, we also supported a Gulf of Mexico operator's forum, allowing the operators to bring presentations to the perforating community regarding their conditions, successes, and concerns.

Behind the scenes, your Board of Directors for the IPFC has been busy working through the processes of setting up and maintaining our non-profit scientific community. Following regulations and mandates from the respective governments and agencies is paramount to the transparency our sponsors deserve and the health of the organization. With this in mind, we solicited the resources of our legal counsel and a certified accounting firm to insure we are following the reporting and compliance requirements in every aspect. These processes included the adoption of by-laws, organizational appointments, and our first tax return filing as a 501c(6) entity.
Soon you will see additional documents under the "ABOUT US" tab on the perforators.org website. These documents are required under the umbrella of the non-profit status, to be included in our by-laws, but the board feels they are important enough to post to the website for the review of all.

While 2017 will not be quite as busy a year on the symposium front, activity continues on the advancement of the organization. Website advertisement has been made available and plans have already begun for upcoming events in the North America, and Asia Pacific regions. Stay tuned to the perforators.org website for announcements, advertisements, and the advanced technical content you have come to expect.

On behalf of the Directors of the IPF,
John Segura
Treasurer, International Perforating Forum Co.
10 July 2017

JIPF EXECUTIVE EDITORS

EDITORS' MESSAGE

John Carminati

Brenden Grove

Welcome to the second issue of the Journal of the International Perforating Forum. This issue follows an extremely busy year within the IPF and the perforating industry at large, despite the O&G industry's biggest downturn in at least a generation. As the industry strives to do more with less, technology is becoming more essential in the pursuit to continually increase E&P efficiencies, improve safety, reduce risk, and minimize cost per barrel recovered. Indeed technology is enabling some field developments to become economical in this "new normal". Considering the central role perforations play in the ultimate production system, readers of this publication will no doubt appreciate that good perforating practices can be the difference between viable and non-viable developments.

Against this backdrop, it is perhaps appropriate that this issue of the JIPF features two articles on perforation modeling. Modeling is important in areas where well count is limited and offset completion practices cannot be adequately analyzed. A good model can be an important component of the overall effort to compare alternatives, weigh expectations, and engineer the perforating event. Although created as an official entity only recently, the IPF traces its roots back almost a decade to the organizing committee of the 2008 IPS in the Woodlands. Since these beginnings, the IPF has continued to strengthen the global perforating community by organizing periodic international and regional symposia, safety forums, and more recently building our website, publishing the JIPF, and introducing the CE and YP initiatives with the goal to infuse our community with new thoughts, theories and capacity to conduct scientific investigation. In late 2016, the IPF supported a GoM forum. One theme was stress caging and its impact on penetration performance. As a perforating community, we are trying to improve our understanding of this topic. However, because of the current industry cycle, we are doing this in a declining expertise and tightened budget environment.

In the current industry environment, we must continue to strengthen the perforating community, as well as our links with the drilling, completions, & production communities. It is therefore essential that we expand our reach beyond "us talking to us". We need to make sure that our colleagues in these related domains know about the IPF, about perforators.org, and understand how these resources can benefit them and the industry at large. So we appeal to you all to spread the word about the IPF to your colleagues who may currently sit outside of the immediate perforating community.

Finally we wish to thank all who made this issue possible; in addition to the content providers named throughout, this Journal would not exist without the technical editors, reviewers, and the organizations that support them.

J. Carminati & B. Grove

CONTINUING EDUCATION

Welcome to the Continuing Education section. Please visit our website (https://perforators.org/continuing-education/) if you have not done it yet! We have included some technical publications on perforating we hope you will find interesting.

There is also a list of Perforating SPE/OTC papers archived under the same sections of IPF technical workshops, to simplify your search in OnePetro.

We have invited colleagues from many companies to keep growing the list with their recommended papers. During Q3 2017 we plan to conduct some webinars; David Ayre and Kenneth Goodman have graciously volunteered for the first two. Please let us know what other needs you think we should address under Continuing Education, by emailing education@perforators.org

A. Fayard

Alfredo Fayard

YOUNG PROFESSIONALS

In 2016 the IPFC began a Young Professionals group for members within the perforating industry. This recent downturn has proven that the need to maintain a high level of experience in our industry is critical. One of the ways to maintain this is by developing our younger generation of employees and enabling them to connect and learn from previous and experienced generations. Our industry is a "boom or bust" one and we need to make sure there is a future that is capable of supporting our industry, even in the bust.

The YP group would like to invite all individuals under the age of 35 to join and participate. The organization is focused on not only connecting current YP to senior members in our industry, but also as a link between the next generation of individuals and our community. This will include social gatherings, university outreach, and continuing education. It is the desire of the group to dedicate time and resources at future conferences to connecting the YP to the industry.

Our YP group is still just beginning and we have quite a bit to still work out. The benefit to the group is we are looking to reach out and connect with other YP to make this a group that truly fits our needs. We need to know what the YP community needs and wants, so we know how to focus our efforts. We highly encourage any interested to join in and participate and make this successful. We cannot do it without other YP and those who are able to mentor and provide valuable experience. Please send us an email at yp@perforators.org if you are interested.

S. Geerts & C. Sokolove

Shaun Geerts

NEWS

NEWS.

2016 OPERATORS MEETING

The inaugural International Perforating Forum – GoM, hosted by Shell, was held at the OMNI Houston Westside on October 27, 2016. This event was possible due to the organizational efforts of Cam Le with the support of the IPFC executive committee members Mark Brinsden and John Segura. Funding was provided by Shell, International Perforating Forum, Halliburton, Expro, and Schlumberger. Attendance of over 36 distinguished professionals and SMEs from 10 local companies (Shell, BP, Chevron, BHP, Anadarko, Halliburton, Schlumberger, Baker, Expro and Weatherford) participated at the Forum. A new format was implement to encourage open discussions and knowledge sharing. Sessions were structured by having an operator present followed by a service provider to have both perspectives heard before Q&A/ forum, in which ample time was allocated for debate. Topics were centered around Stress Cage Perforating, STIM applications in GoM, and Perforating Dynamics. Stress Caging was the hot topic of the Forum, so much that 2 sessions were dedicated for this challenge facing operators in the GoM. In short, stress caging is defined as a drilling technique used to mitigate loss circulation that would increase the fracture gradient/stresses near wellbore of the formations in order to get to target depth. This leaves behind a large damage zone that perforating must overcome to aid the frac placement. All presentations centered around these discussions as well as the other session will soon be available on perforators.org but attendance is a must if you wanted to capture the lively debates.

Cam Le

Another IPF GoM operators forum is being planned for early August 2017. We will review the issues previously discussed, namely stressed cage drilling effects on perforating, plus present other topics (looking for suggestions – maybe frac charges: benefits / issues). Stay tuned for further details on the agenda and location, which will be determined closer to the event. Beyond this, we are also considering working with operations locations such as Midland to host a local event.

Phil Crabtree

REGIONAL UPDATES

NORTH AMERICA

The organizing committee is pleased to announced the next IPS will be held at Moody Gardens in Galveston, TX; July 29 – Aug 2, 2018. Mark your calendars and stay tuned to perforators.org for more details.

Alphie Wright & John Carminati

LATIN AMERICA

During 18-20 October 2016, Symposio Lationamericano de Perforating (SLAP 2016) was held in Buenos Aires, Argentina. For the first time, Argentina was selected to be the venue for the symposium. 36 submissions for technical presentations were received. There was high attendance that exceeded organizers expectations and active participation of main operators and service companies. 97 attendees, 21 technical presentations and 5 technical posters in addition to Showroom and the always beneficial exchange of technical information, were the result of the symposium.

Santiago Colacelli

Discussions are currently underway toward organizing SLAP 2018 in Bogota, Colombia

MIDDLE EAST

The Third MENAPS was held in Muscat Oman during 13-14 November 2016 with a total attendance of 107. Within 2 days 25 technical presentations including testing, design and operations challenges of perforation business had been efficiently presented and transferred the knowledge to the ME region users. 10 presentations are from Oman and 15 are from abroad. Local news papers Muscat Daily and Alwatan published the symposium simultaneously and PDO published MENAPS 2016 in Al-Fahal magazine in April 2017. Oman attendees acknowledged and highlighted the value of the event

الوطن

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مسقط ـ "الوطن":

تاريخ النشر: 15 نوفمبر,2016

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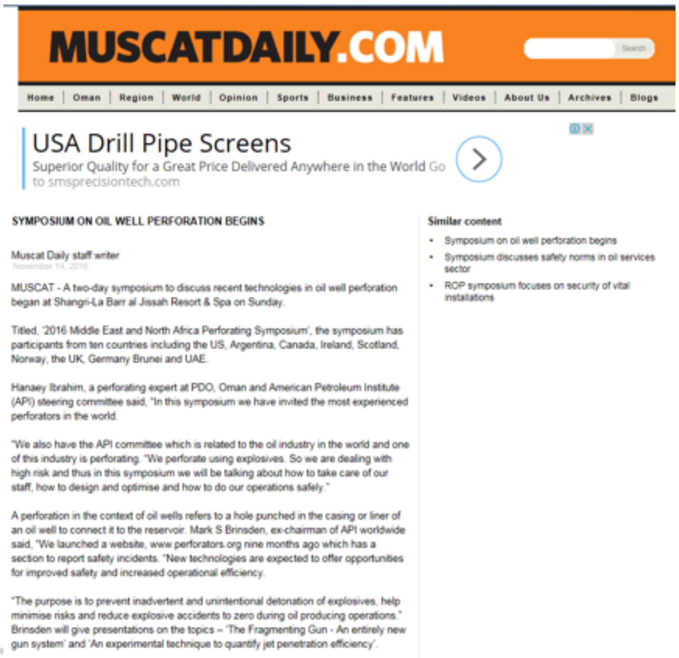

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SYMPOSIUM ON OIL WELL PERFORATION BEGINS

Muscat Daily staff writer
November 14, 2016

MUSCAT - A two-day symposium to discuss recent technologies in oil well perforation began at Shangri-La Barr al Jissah Resort & Spa on Sunday.

Titled, '2016 Middle East and North Africa Perforating Symposium', the symposium has participants from ten countries including the US, Argentina, Canada, Ireland, Scotland, Norway, the UK, Germany Brunei and UAE.

Hanaey Ibrahim, a perforating expert at PDO, Oman and American Petroleum Institute (API) steering committee said, "In this symposium we have invited the most experienced perforators in the world.

"We also have the API committee which is related to the oil industry in the world and one of this industry is perforating. "We perforate using explosives. So we are dealing with high risk and thus in this symposium we will be talking about how to take care of our staff, how to design and optimise and how to do our operations safely."

A perforation in the context of oil wells refers to a hole punched in the casing or liner of an oil well to connect it to the reservoir. Mark S Brinsden, ex-chairman of API worldwide said, "We launched a website, www.perforators.org nine months ago which has a section to report safety incidents. "New technologies are expected to offer opportunities for improved safety and increased operational efficiency.

"The purpose is to prevent inadvertent and unintentional detonation of explosives, help minimise risks and reduce explosive accidents to zero during oil producing operations." Brinsden will give presentations on the topics – 'The Fragmenting Gun - An entirely new gun system' and 'An experimental technique to quantify jet penetration efficiency'.

Similar content

- Symposium on oil well perforation begins
- Symposium discusses safety norms in oil services sector
- ROP symposium focuses on security of vital installations

Safety Tops Agenda At MENAPS

PDO has played a leading role in a two-day symposium to discuss recent technologies in oil well perforation.

The Middle East and North Africa Perforating Symposium (MENAPS) at Muscat's Shangri-La Barr Al Jissah Resort drew participants from 10 countries including the US, Argentina, Canada, Ireland, Scotland, Norway, the UK, Germany Brunei and the UAE.

Hanaey Ibrahim addresses the MENAPS event

There was positive feedback from many attendees from operating companies in Oman, such as Oman Oil, MEDCO, Petrogas, Occidental, as well PDO. There were more than 100 participants in the technical discussions and PDO led seven out of the 25 presentations.

PDO Perforation Subject Matter Expert Hanaey Ibrahim, a member of the Oman and American Petroleum Institute (API) steering committee said: "We invited the most experienced perforators in the world to MENAPS.

"We perforate holes from the well casing into the reservoir using explosives, so we are dealing with high-risk activity. During the event, we spoke about how to take care of our staff, how to design and optimise and how to conduct our operations safely.

"We also discussed the latest updates in API recommended practice, new perforation technology and tests, and had an open discussion about challenges encountered in perforation completion with operating companies."

PDO also hosted two experts: Shell Global Perforation Led Mark Brinsden, API Chairman and International Perforating Forum President, and Shaun Geerts, Engineering Manager-Testing Solutions, Owen Oil Tools and API committee member.

Mr Brinsden said, "New technologies are expected to offer opportunities for improved safety and increased operational efficiency.

"The purpose is to prevent inadvertent and unintentional detonation of explosives, help minimise risks and reduce explosive accidents to zero during oil producing operations."

Al Fahal | March 2017

Hanaey Ibrahim

RUSSIA

Dear Perforating Industry Member,

On behalf of the RIPS Organization Committee it has been decided to hold the 2017 RIPS – Russia International Perforating Symposium in Tyumen on October 23rd to 25th, 2017 at the DoubleTree by Hilton Hotel. This event, while being exclusively organized by the Russia International Perforating Symposium, will follow the format and guidelines of other global IPFC symposia. Presentations will be held in English and Russian, with simultaneous translations scheduled during the entire event. The call for papers, as well as the sponsorship program will be published in due course. In case of any questions, please do not hesitate to contact us under mailto:rips@dynaenergetics.com.

Frank Preiss

ASIA PACIFIC

I am pleased to report that the process for hosting the next Asia Pacific - Perforating Symposium (APPS) has begun and is scheduled for Q1 2018. The committee is currently being staffed, and has already obtained early commitments from service companies, manufacturers, and well operators. As in past forums, the event is expected to coincide with OTC Asia, in Kuala Lumpur, Malaysia. We hope to obtain a broad base of participation as the market begins to slowly recover.

If you have an interest in volunteering on the 2018 APPS Committee, to further promote the innovation, application, and further advancement of perforating technologies, please contact me at mailto:Clinton.quattlebaum@halliburton.com

Clint Quattlebaum

EUROPE

A committee has been formed, headed by Frank Preiss and Sandra Binar, to organize the next IPS-Europe. Current plans are for Nov 2017 in Hamburg, Germany. Mark your calendars, stay tuned to perforators.org, and look for further communications from the organizers in the near future.

MULTI-SCALE MODELING FOR DAMAGE CHARACTERIZATION AND PRODUCTIVITY PREDICTION AROUND A PERFORATION TUNNEL

Authors:

Rajani P. Satti, Baker Hughes, IPF Member
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Stephen N. Zuklic, Baker Hughes, IPF Member
Nils Koliha, Exa Corporation
Ryan Jew, Exa Corporation
Bernd Crouse, Exa Corporation
David Freed, Exa Corporation

Biographies

Rajani P. Satti, Baker Hughes, IPF Member

Dr. Rajani Satti is Product Manager for Perforating and Reservoir Sciences at Baker Hughes. He received his M.S in Mechanical Design from Kettering University and his doctorate in Mechanical Engineering from University of Oklahoma. He has been with Baker Hughes since 2010 and is primarily involved in technology management, perforation testing/modeling and related reservoir applications. He is active with SPE and industry consortiums and is an author and co-author on over 25 SPE papers covering computational fluid dynamics, perforating and production optimization.

Derek S. Bale, Baker Hughes, IPF Member

Dr. Derek Bale holds Bachelor of Science degrees in both Engineering Physics and Applied Mathematics from the University of Colorado, as well as a PhD in Applied Mathematics from the University of Washington. He has developed physics-based models and numerical algorithms in the astrophysics, semiconductor, and more recently Oil & Gas communities for the past twenty years. At Baker Hughes, Dr. Bale manages the Applied Science group within the Intelligent Production Systems product line. He is currently working on various problems in fiber optic data analysis & interpretation, shock modeling for perforation job design, the swell dynamics of elastomer packers, and fast computational techniques based on multiple-scale asymptotics.

MULTI-SCALE MODELING FOR DAMAGE CHARACTERIZATION AND PRODUCTIVITY PREDICTION AROUND A PERFORATION TUNNEL

Stephen N. Zuklic, Baker Hughes, IPF Member

Stephen Zuklic has worked for Baker Hughes since entering the oilfield in 1993. He has served in field engineering, applications support, technology and product development, sales and marketing and operations management. He has specialized in completions including cased hole and open hole sand control, tubing conveyed perforating, drill stem test tools, packer systems and subsurface safety systems. He has worked in regional and global roles. Currently serving as global product line manager for TCP-DST since 2010, he is active on the API-RP19B subcommittee and International Perforating Forum. He has actively authored multiple industry papers and holds multiple patents as well as directing the global training programs for Baker Hughes TCP and DST.

Nils Koliha, Exa Corporation
Ryan Jew, Exa Corporation
Bernd Crouse, Exa Corporation
David Freed, Exa Corporation

MULTI-SCALE MODELING FOR DAMAGE CHARACTERIZATION AND PRODUCTIVITY PREDICTION AROUND A PERFORATION TUNNEL

Rajani Satti, Derek Bale, Stephen Zuklic, Baker Hughes
Nils Koliha, Ryan Jew, Bernd Crouse, David Freed, Exa Corporation

SUMMARY

Perforated completions play a crucial role in efficient hydrocarbon recovery as well as long-term well productivity. However, perforating often alters formation permeability around the perforation tunnel that, along with other perforation parameters (e.g., penetration depth, hole size, and shot configuration), significantly impacts the near-wellbore pressure drop and production. Standard numerical or inflow production models are based on many assumptions involving tunnel geometry and damage characteristics. This approach can lead to discrepancies between estimated and actual productivity of the tunnel, thereby affecting the overall completion planning through the life of the well.

In contrast to previous studies, the production flow model presented in this work leverages the perforation flow laboratory, conventional computerized tomography (CT) and micro-CT, and most importantly, a multi-scale simulation approach to provide an improved prediction of productivity. The multi-scale simulation method discussed here integrates pore-scale modeling with traditional Computational Fluid Dynamics (CFD). This full-scale three-dimensional flow model accounts for realistic aspects of tunnel geometry, perforation damage, and blockages that impede the flow.

The simulation-based approach facilitates a detailed understanding of the competing effects of perforation damage, tunnel plugging, and overall shape and size of the tunnel by isolating these effects, which is impractical in a laboratory setting. Whole-field flow visualization including fluid velocities, streamlines, pressures, and most importantly, resulting productivity ratios are presented. This work enables the implementation of a multi-scale simulation approach as a practical engineering tool that can be used to provide a realistic prediction of downhole productivity. This insight can eventually provide information that enhances the decision-making process of a perforated completion design.

INTRODUCTION

In well completions, perforation tunnels represent the conduits through which all communication with the reservoir takes place, including treatment and production operations. The complex fluid dynamics surrounding these tunnels has been a subject of many research studies. In particular, the flow efficiency of perforation tunnels is critical for determining the economics of a completed well. Given the harsh conditions in the downhole environment, it is very challenging to obtain real-time measurements of tunnel performance. In recent years, perforation flow laboratories (Grove et al. 2011, Grove et al. 2012, Halleck 1997, Brooks et al. 2011) have been increasingly used to study perforation systems and their flow effectiveness in more detail (using API RP-19B Section 2 and 4). However, experiments often become challenging due to large lead times in performing tests, associated costs, and most importantly, limited data. As a consequence, numerical tools have been increasingly used in conjunction with experiments to provide better insight into the flow characteristics of perforated cores and perforated well-scale formations.

Several numerical studies on perforation fluid flow have been conducted for core scale (Behie and Settari, 1993, Roostapour and Yildiz, 2005) and well-scale scenarios (Tariq, 1987, Sun et al., 2011). Most numerical modeling on perforation systems has been based on semi-analytical studies, nodal analysis and CFD studies. Of relevance to our study was the recent work of Sun et al. 2011 and 2012, who focused on developing and validating well-scale and lab-scale perforation models using Computational Fluid Dynamics. However, the above studies lack the following aspects that are critical to predicting the productivity of perforated completions:

- True geometry of the tunnel rather than approximation of cylindrical or conical shapes.
- Characteristics of damaged zone (thickness and physical properties of the damaged zone) around the perforation tunnel. In fact, standard inflow models routinely assume that the permeability of the damaged zone is 10% of the native rock permeability.

Motivated by the above, this study utilizes the capabilities of the flow laboratory in conjunction with multi-scale flow modeling to simulate the true geometry and damage around a perforation tunnel and provide insight into the flow performance of a perforation tunnel. This flow model accounts for realistic aspects of tunnel geometry, perforation damage, and blockages that impede the flow. The flow laboratory is used first to conduct a standard API RP-19B Section-4 test to obtain a perforated core. Subsequently, the perforated core is used to conduct a multi-scale flow performance analysis, where CT and digital rock physics are leveraged to conduct micro-scale pore flow analysis. The results can be considered a first-order incorporation of the damage and flow mechanism around the tunnel. Higher order effects including the influence of zero stress on extracted rock samples, 3D flow rather than the axial flow and variations in core cutting procedures are not investigated in detail.

PERFORATION FLOW LABORATORY

The perforation flow laboratory (**Fig.1**) is configured to provide perforation and flow testing as described in API Recommended Practice 19B and conform to the latest industry standards of Section-II and IV procedures. The flow laboratory provides the capabilities to study and qualify performance of different perforating systems in formation rock at reservoir conditions, influence of various factors on well productivity, and integrate this knowledge to develop a state-of-the-art perforation evaluation and design service. This in turn, enables us to design and qualify perforating solutions with the goal to optimize reservoir performance.

For the current study, a shaped charge was considered to create a perforation tunnel around a sandstone Berea rock. As already mentioned above, we are primarily interested in demonstrating how digital rock physics along with traditional CFD methods are used to develop a production flow model. After an API Section-IV test is conducted, the perforated core is scanned using conventional CT (resolution ~1.25mm) to obtain a representation of the size, shape and depth of penetration. More details on the flow laboratory were recently discussed by Osarumwense et al. 2014. It should also be noted that the flow laboratory experiments are based on linear (or axial flow) through the perforation geometry. Although the simulation methodology provides the capability to model axial and/or radial flow, the current study assumes axial flow through the perforation tunnel geometry. Test parameters utilized in the flow laboratory are listed below:

- Pore pressure = 6000 psi
- Wellbore pressure = 5500 psi
- Overburden pressure = 9300 psi
- 4-1/2" gun system with a 39 gram deep penetrating shaped charge
- Odorless mineral spirit was used as the working fluid
- Core properties, 7" dia and 30" length Berea core, average porosity~20% and average permeability ~ 180 mD

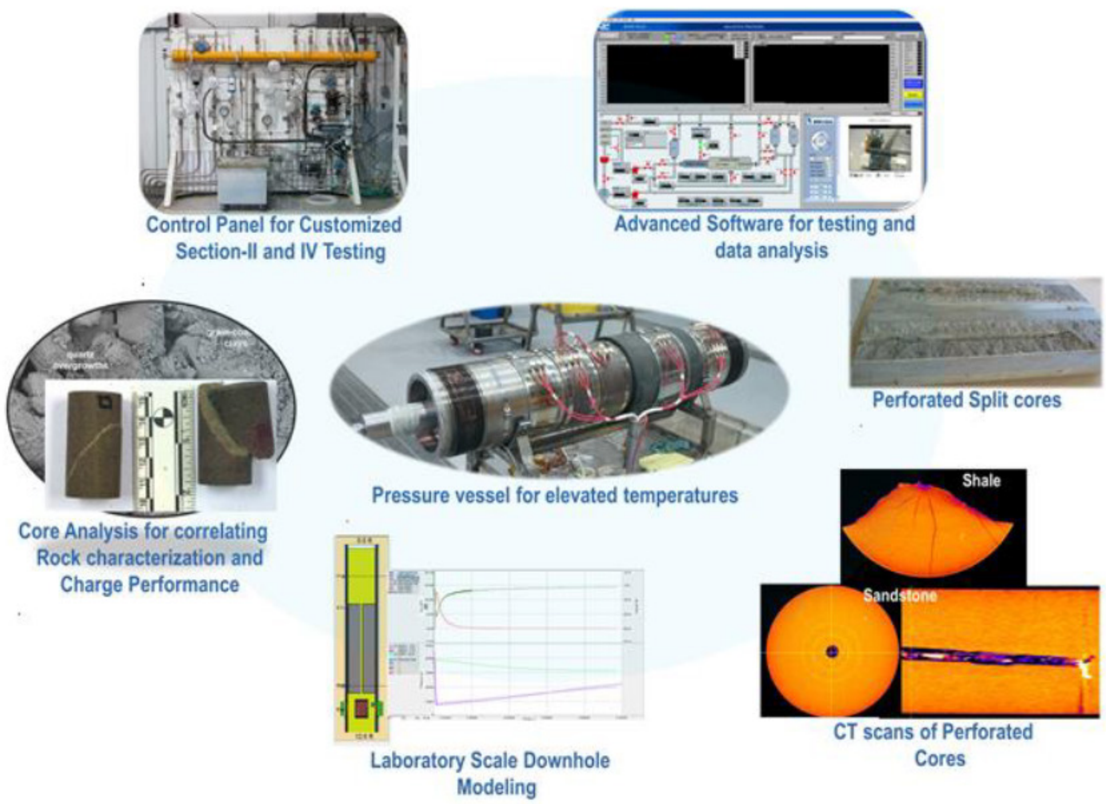

Fig. 1. Elements of the Perforation Flow Laboratory

COMPUTATIONAL APPROACH

Commercially available flow simulation software (PowerFLOW 5.4), based on the lattice Boltzmann method (LBM), is used to calculate the flow in the test section domain. Lattice-based methods, an alternative to traditional CFD methods, track the advection and collisions of fluid particles on a computational lattice (grid). Because the average number of particles per grid cell far exceeds the computing power required to track them individually, the particles are grouped into an integer number of discrete velocities. LBM has been well validated and is in common use for many flow applications. The flow solver used here includes a turbulence model that is conceptually similar to the large-eddy simulation approach. The flow solver also includes a porous media model that is used in this study to model the rock (Freed 1998). The porous media model invokes a Darcy-type pressure loss by applying a flow resistance determined from the known permeability of the rock. The resistance can include a viscous (linear) and an inertial (quadratic) term with respect to local velocity, and can be made to vary spatially to model rock heterogeneity which, in this case, is used to model the decreased permeability in the damaged zone.

It should also be noted that the focus of the study presented here is to evaluate the feasibility of the digital rock method to provide insight into the complex characteristics of the damage zone and relate those properties to productivity. A comprehensive validation of the model within the context of controlled flow laboratory experiments is being carried out and will be reported elsewhere.

SIMULATION WORKFLOW

A complete workflow as illustrated in **Fig. 2** was developed to characterize perforation damage and compute productivity. The workflow consists of the following steps:

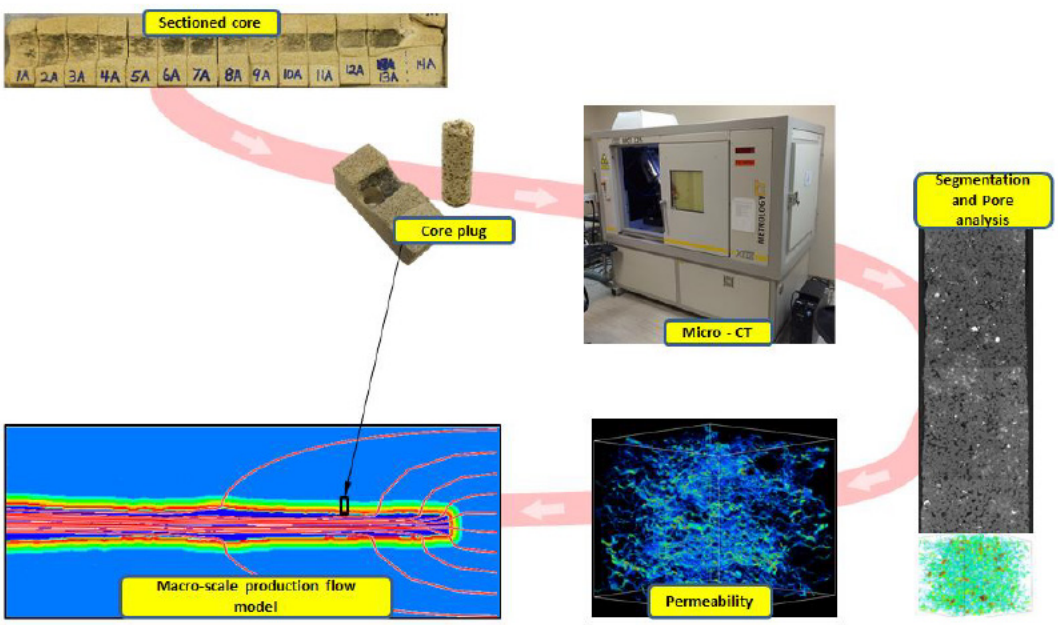

Fig. 2. Computational workflow utilized for the multi-scale simulation study

1. Perforate a core (Berea sandstone) under in-situ conditions and conduct a conventional CT scan to measure the hole size and depth of penetration.

2. The perforated core is partitioned into smaller core sections (numbered from 1A to 14A in **Fig. 2**).

3. Smaller core sections can be selectively chosen depending upon the area of interest, from which cylindrical core plugs are carefully drilled using a precision drill bit. Each core plug will typically include the tunnel surface, the damage zone and the native formation domain. For the purpose of this study, section 5A was chosen for the analysis.

4. Micro-CT scanning is then performed on each core plug to obtain a high-resolution (~2 to 4 micron) 3D image.

5. Image segmentation is then performed on the 3D tomographic images to generate the pore space geometry.

6. Analyses are performed to characterize the pore space, including calculations of porosity and pore size distribution throughout each sample.

7. The geometry is then input into LBM flow simulations to compute effective permeabilities throughout each sample.

8. The resulting porosity and effective permeability information are used to characterize the perforation damage (physical properties and thickness of damage), which is then used as input for advanced CFD production flow modeling. Influence of the perforation tunnel, damage zones and plugging at the toe section on overall productivity are investigated in detail.

PERFORATION DAMAGE CHARACTERIZATION

As discussed above, the extracted core plug 5A (2.189 x 2.189 x 2.036 mm^3, pixels=912x912x848 @ 2.4 um/pixel) was first scanned using micro-CT to obtain a 3D tomographic image. The plug was imaged by a series of 4 scans at a resolution ~2.4 µm, with the scans partly overlapping to enable a continuous reconstruction. Image-processing techniques were then applied to segment the images into grain vs.pore regions to provide a geometric representation of the pore space.

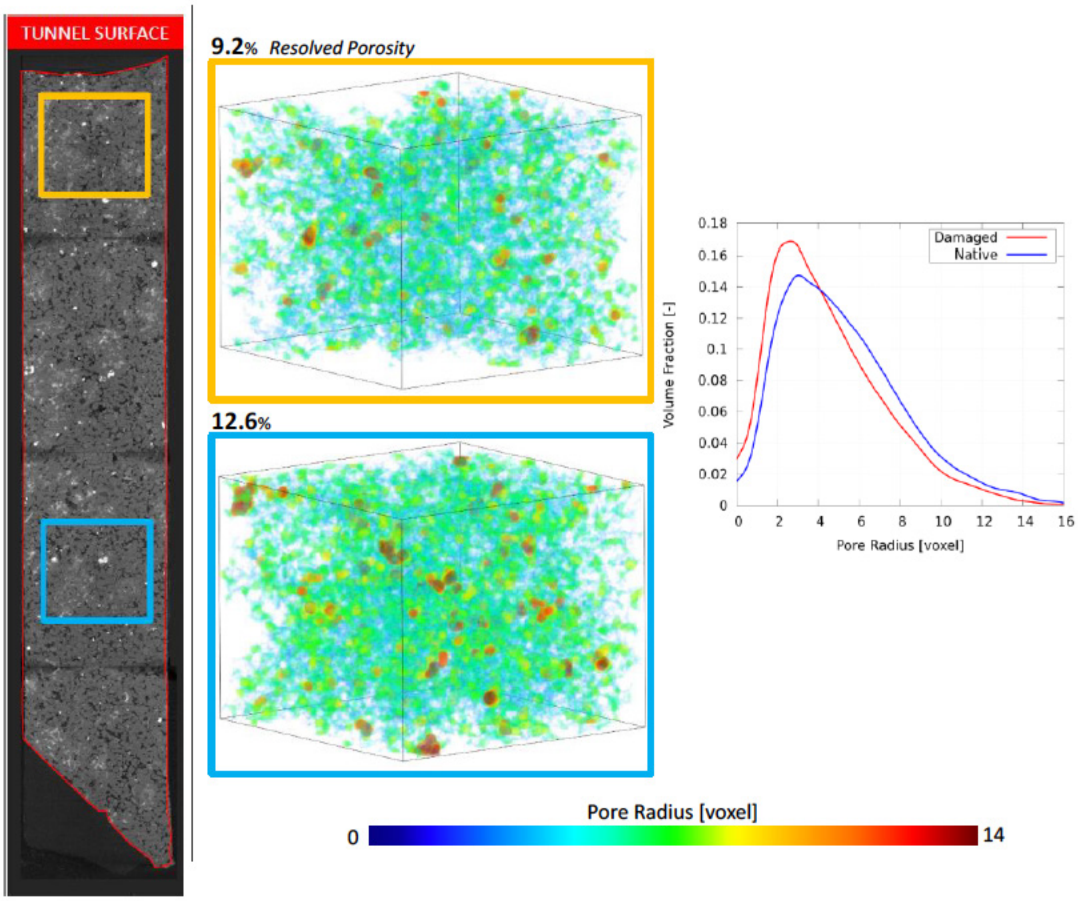

Fig. 3. 3D visualizations of pore size distribution in damaged and native zones

Fig. 3 shows the center-planes of the reconstructed micro-CT images from the test section plug, along with three-dimensional visualizations of pore size (radius) distribution as determined using a typical maximum sphere method. Pore size visualizations are shown for the damaged (yellow) and native (blue) regions for the core plug. For the plug, the impact of the shaped charge jet on the pore structure of the tunnel surface region is clearly observed, with fewer large pores (red color range) and more small pores (blue color range) seen in the damaged regime. This is consistent with overall resolved porosity calculated as 9.2% for this damaged zone region compared to 12.6% for the native zone region. Pore size distributions for native and damaged rock are also quantitatively compared in **Fig.3,** which plots the volume fraction of pore space versus pore radius. The shift to the smaller pores in the damage zone is clearly evident.

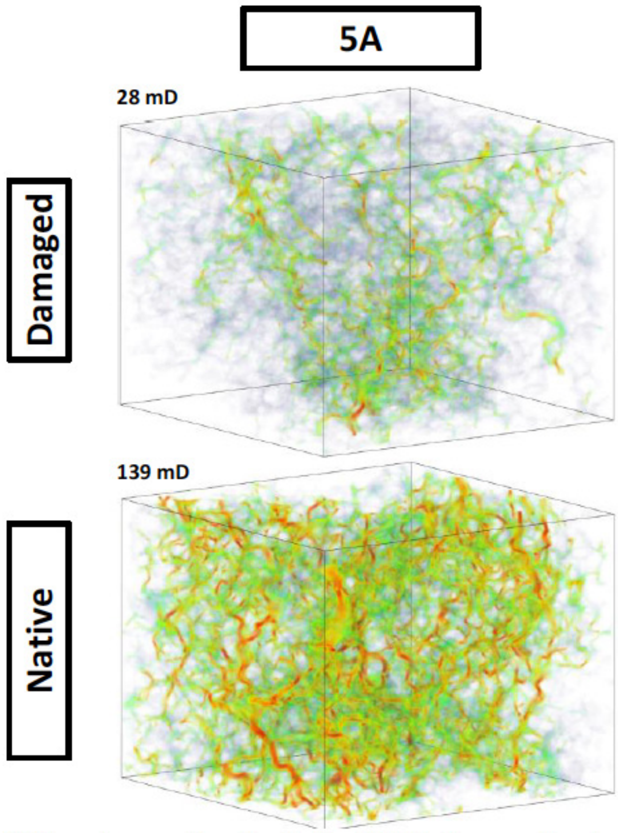

Fig. 4. Whole field contours of local velocity field in damaged and native zones

Following the characterization of the pore space, flow simulations were conducted using the Lattice Boltzmann method to compute an effective permeability. **Fig. 4** shows the local velocity field for the same regions shown in **Fig.3**, using opacity to emphasize the high-velocity locations. The logarithmically varying color range is consistent for both the images, i.e., the local velocity is normalized by the same overall maximum value. The overall flow in the damaged rock is reduced compared to native rock, with the computed permeability variations from damaged to native zone of 30mD to 139mD. Fewer connected paths remain in the damaged zones, thereby adversely affecting the flow conductivity. This decrease in flow conductivity in the damaged region can significantly affect the inflow of hydrocarbons through the tunnel.

In **Fig.5,** the smoothed profiles of porosity and permeability are plotted for the plug and superimposed on the reconstructed center-plane scan images. The x-axis gives the distance from the tunnel surface towards the native rock. The y-axes show permeability and porosity. For the plug, the smoothed data suggests a damage zone thickness of ~11mm, with porosity varying from 9% (in the damaged zone) to 13% (in native zone). The permeability changes from 30mD (in the damaged zone) to 160mD (in native zone). The permeability variation is well correlated with the porosity, although further parametric studies are required to quantify any specific relationship between the two in general.

Again, such information about localized porosity/permeability values is almost impossible to measure in a laboratory setting, thereby emphasizing the capabilities and value of the digital rock methodology.

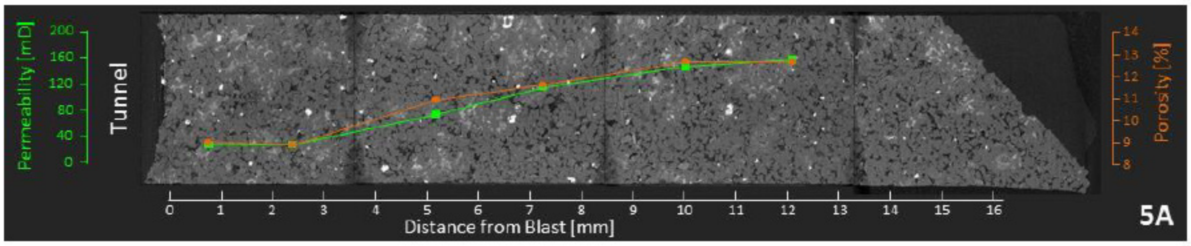

Fig. 5. Profiles of Porosity and Permeability

MULTI-SCALE PRODUCTIVITY ANALYSIS

In this section we discuss the results obtained from implementing a multi-scale simulation approach (digital rock physics for micro-scale analysis combined with macro-scale traditional CFD) to model productivity as well as evaluate competing physical effects around the tunnel. As discussed earlier, based on the Section-IV test, the 3D perforation channel geometry was created using conventional CT scanning to represent a realistic physical model for productivity analysis. The resulting CAD geometry of the tunnel is shown in **Fig. 6.** Flow simulations using this geometry were conducted using the LBM-based solver with porous media model. The model properties used in all simulations can be found in Table 1.

Table 1. Model properties

Core radius	3.5 in.
Core length	30 in.
Core permeability	180mD
Core Porosity	15 %
Working fluid	Water
Boundary conditions	Fixed pressure simulating a pressure drop of 200psi from inlet to outlet

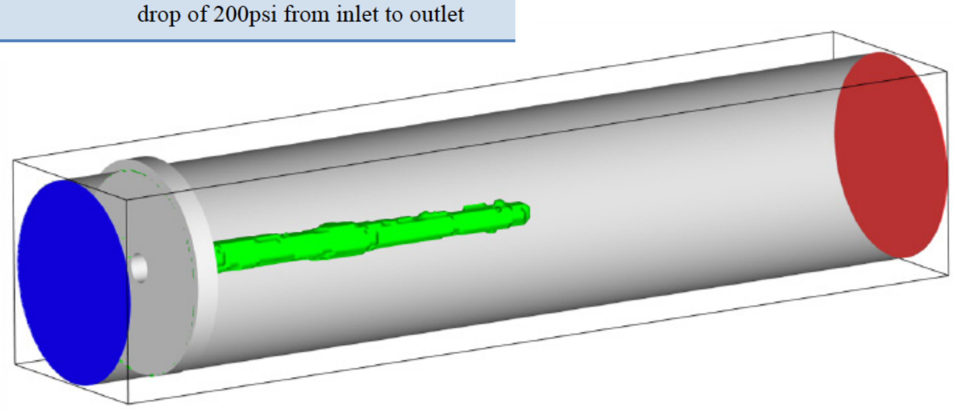

Fig. 6. Computational domain used for the macro-scale flow simulations

Five computational models (as shown in **Fig.7**) for different scenarios were developed for the productivity analysis:

Case 0: Cylindrical formation core with permeability of 180mD, no casing

Case 1: Cylindrical formation core with a hole in the casing

Case 2: Realistic perforation tunnel generated from a Section-IV test

Case 3: Realistic perforation tunnel generated from a Section-IV test, accounting for damage (permeability ~30mD and damaged zone thickness ~10mm) around the tunnel based on Digital Rock analysis

Case 4: Realistic perforation tunnel generated from a Section-IV test, accounting for damage around the tunnel, and including the influence of toe plugging from charge debris

Table 2 shows the computed productivity ratios for all scenarios. As expected, the productivity ratio was significantly reduced for case 1 compared to case 0 because the flow was restricted by the casing plate. With the inclusion of the true geometry model of the perforation tunnel, the productivity ratio was significantly increased to 1.7 (primarily due to the free flow path within the tunnel and the increased surface area available for flow). Next, the data from the digital rock analysis was included for case 3 to account for the damage zone thickness and permeability. For case 3, the simulated productivity ratio was reduced to 1.6. Finally, case 4 included the effect of a slug around the toe to represent the shaped charge debris slug that is often observed in experiments. The productivity for this case was further reduced to 1.5. These results highlight the importance of including realistic attributes of the perforation tunnel and clearly show the competing effects of debris, damage, and toe plugging on the flow efficiency and overall productivity of the perforation tunnel. Such insight, provided by isolating the effects of perforation tunnel attributes is impractical to achieve in a flow laboratory or using standard inflow or CFD models. Table 2 also provides a representative productivity from an example 6SPF gun system in STB/day.

Fig. 7. Scenarios of various flow models considered for analysis

Table 2. Productivity ratio comparisons for different tunnel scenarios

Case	Productivity	System Productivity (6SPF)	Productivity Ratio
0	3.55 l/min	193.6 STB/day	1.0
1	2.71 l/min	147.8 STB/day	0.7
2	5.95 l/min	325.6 STB/day	1.7
3	5.67 l/min	309.2 STB/day	1.6
4	5.29 l/min	288.5 STB/day	1.5

In the following section we present more details on the flow characteristics for cases 3 and 4. **Fig. 8** shows center-plane flow contours of normalized velocity, pressure and pressure gradient for cases 3 and 4. The velocity contours show the influence of plugging effects at the toe of the tunnel, whereby a stagnation zone around the plug is observed for case 4. As expected, peak velocities are evident around the center region of the tunnel. Nearly the entire pressure drop occurs from the inlet to the toe. For both cases, the flow is concentrated at the toe of the tunnel, causing highest pressure gradient. However, the extent of the highest pressure gradient is more pronounced for case 3 when compared to case 4. It is also interesting to see the distribution of a fairly high pressure gradient in the damaged zone of the tunnel.

Fig. 9 shows the flow streamlines for case 3 and case 4 overlapped on each other. The flow fraction for the flow paths is also shown on the right side. Introducing the plug to the toe of the tunnel shifts the flow entry downstream, with 31% of the flow converging towards the center of tunnel. **Fig. 10** shows the variation of tunnel flow rate along the length of the tunnel for different cases. The presence of damage zone moves the tunnel flow entry downstream and the presence of the plug strengthens this effect.

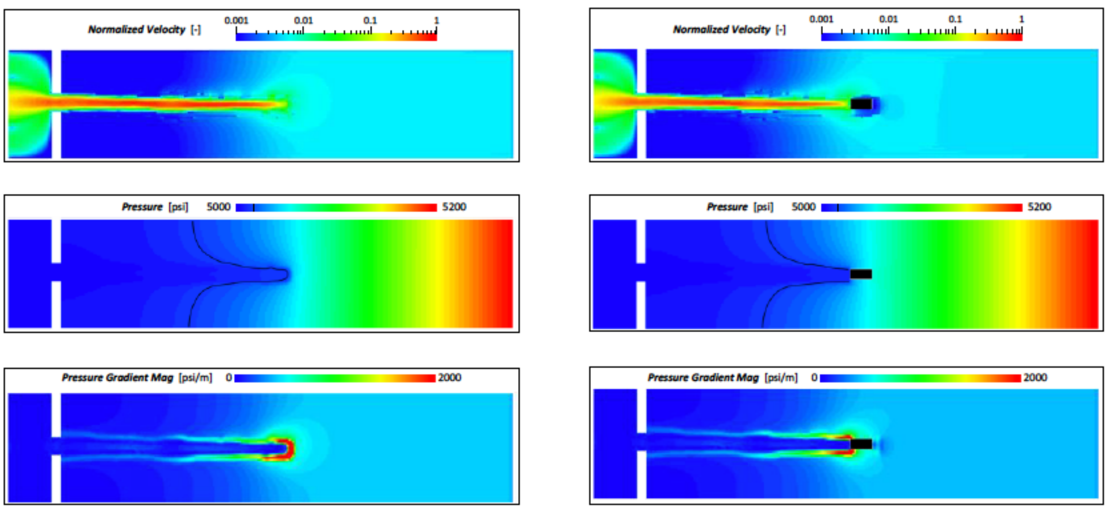

Fig. 8. Whole-field contours of velocity, pressure and pressure gradient, case 3 (left) and case 4 (right)

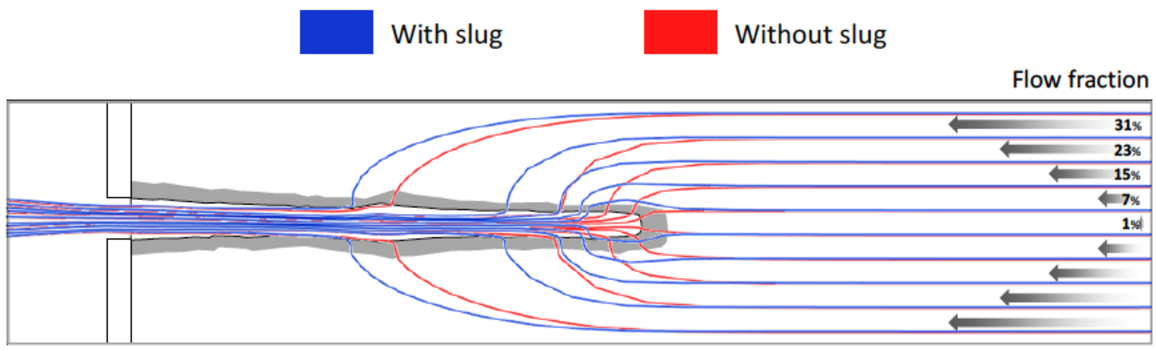

Fig. 9. Overlapped streamline contours, case 4 (blue) and case 3 (red)

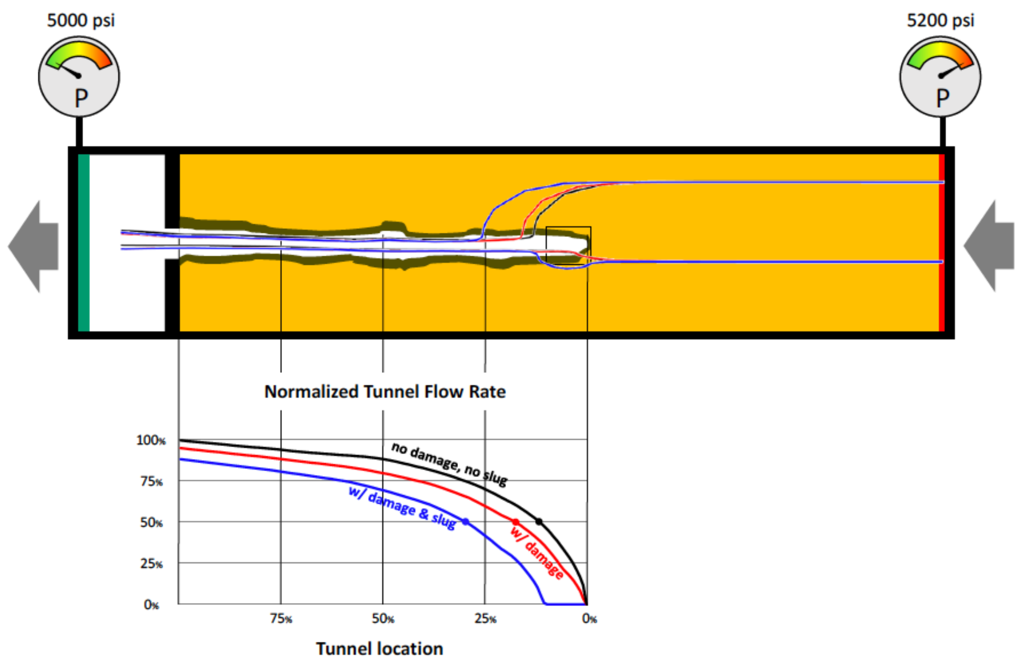

Fig. 10. Comparison of normalized tunnel flow rate along the tunnel for different cases.

CONCLUSIONS

In this study, we developed and demonstrated a multi-scale flow simulation approach to quantitatively predict the perforation damage characteristics and provide insight into the productivity around a perforation tunnel. An API RP-19B Section-IV test was conducted under in-situ conditions and the shot core was considered for computational analysis to predict perforation damage and related productivity. Quantitative details pertaining to the thickness of the damaged zone along with local information of porosity and permeability were presented. Furthermore, this work also demonstrated the process of utilizing the damage zone characteristics and relate to productivity around the tunnel. In summary, this study demonstrates the application of a valuable modeling tool for understanding perforation damage and quantifying the influence of competing parameters like debris, damage or realistic perforation geometry on the productivity.

This insight can eventually provide information that enhances the decision-making process of a perforated completion design.

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ADVANCES IN COMPUTATIONAL MODELING FOR UNDERBALANCED PERFORATING: FROM LAB TO FIELD

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ADVANCES IN COMPUTATIONAL MODELING FOR UNDERBALANCED PERFORATING: FROM LAB TO FIELD

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Baker Hughes

SUMMARY

Perforating with a dynamic pressure underbalance has become a standard technique to provide a clean and unobstructed production link between a cased well completion and reservoir. The design of an optimal cleanup process, however, requires an understanding of complex and interdependent processes, such as the generation of the driving pressure transient within the wellbore, the resulting surge flow within the tunnel, and how this surge flow drives the cleanup mechanism. A significant challenge of any numerical model for this process is that it requires a dynamic coupling of multi-phase flows between the reservoir, perforation tunnel, and wellbore, resulting in long simulation times. Further, optimizing a perforating job design often requires many such simulations, whether for large design parameter matrices, or sensitivity studies on individual parameter sets.

In this work a fast computational model for the post-detonation underbalance pressure transient that drives the cleanup process is presented. The model is based on physics at the right scale, resulting in a computational efficiency up to three orders of magnitude better than other industry standard software. Beyond speed, the benefits of this novel approach include model parameters that are directly related to the flow physics, and therefore the simulation results are easily interpreted for enhanced perforating job design. The transient model predictions are compared to high-speed pressure gauge data from an API-RP 19B Section IV test, and benchmarked against a current industry-standard dynamic simulator. Further, the way in which the present model connects perforation cleanup to job design parameters is quite general by design. Therefore, to demonstrate a specific use case, an example is presented in which the present model is used in conjunction with a classical cleanup model to drive design choices for parameters such as the free gun volume and static underbalance.

INTRODUCTION

In cased hole completions, perforations provide the critical production link between the wellbore and reservoir. Indeed, generating clean and unobstructed tunnels capable of maximizing the flow of hydrocarbons has been a challenge in the oil and gas industry for many decades [1]. As early as the 1950s it was realized that perforating with a hydrostatic pressure in the wellbore that is below the formation pressure (i.e., static underbalanced perforating) improved the perforation cleanup process.

Later, researchers noted additional benefits when using the free gun volume (FGV) to generate an additional pressure differential to drive surge flow through the tunnels (i.e., dynamic underbalanced perforating). The additional surge flow improves the perforation cleanup by flushing tunnel debris and removing damaged rock zones surrounding the tunnel. [2] [3]

A representative dynamic underbalance (DUB) pressure transient is shown in **Fig. 1**. When the charge is detonated, the wellbore pressure rapidly drops by ΔP, and subsequently recovers after a time τ. These are two example characteristics of the transient that influence the strength and duration of the surge flow, and therefore play an important role in tunnel cleanup and productivity enhancement. It follows that the design of an optimal cleanup process requires operational control of at least ΔP and τ, but likely other characteristics of the transient as well. [3] [4] The challenge is, of course, that this requires an understanding of the complex and interdependent processes

Job Design Parameters –› DUB –› Surge –› Cleanup

where the cleanup mechanism depends on the surge flow, which depends on the dynamic underbalance, which, in turn, depends on the choice of job design parameters. Further, all these dependencies are governed by a highly complex fluid dynamic coupling between the reservoir, perforation tunnel, and wellbore.

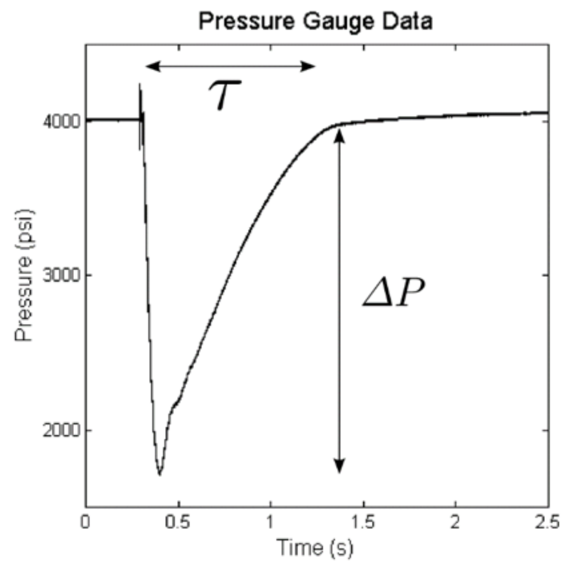


Fig. 1 Dynamic underbalance (DUB) pressure transient just after charge detonation

Nonetheless, researchers have made good progress in describing aspects of the problem. The dependence of a cleanup mechanism on the surge flow was studied by King et al. [5], Tariq [6], and Haggerty et al. [7]. The dependence of the surge flow dynamics on the DUB was studied by Detwiler et al. [8], as well as Bolchover and Walton [4]. However, outside of fully coupled numerical simulations such as those in [9] and [10], studies to date fall short of describing the cleanup mechanism in terms of practical job design parameters. After all, it is these parameters that design and operational engineers can control.

In this paper a fast computational model that describes the DUB transient in terms of relevant job design parameters related to the wellbore, gun system, and reservoir is presented. The model is based on dominant physical processes that drive the pressure transient, resulting in computational times much smaller than industry standard software. Beyond speed, the benefits of this novel approach include model parameters that are directly related to the flow physics, resulting in simulations that are easily interpreted for enhanced perforating job design. Once the model is introduced, simulated results are shown to compare well with high-speed pressure gauge data from an API-RP 19B Section IV test, and then benchmarked against current industry-standard software typically used at the field scale.

Besides capturing the dominant flow physics in an efficient computational model, the results of this study can be used to quantitatively connect job design to perforation cleanup. In fact, the way in which the present model connects cleanup to job design parameters is quite general. Therefore, to demonstrate a specific use case, an example is presented in which the present model is used in conjunction with a classical cleanup model to drive design choices for parameters such as the free gun volume and static underbalance.

PERFORATION FLOW LABORATOTY

The API-RP 19B Section IV test setup shown in **Fig. 2** provides a clear vehicle to study the coupled effects between DUB transients and actual job design parameters. **Fig. 2a** is a picture of the experimental chamber used in our laboratory to measure critical quantities such as pre- and post-perforation permeability, high-speed pressure gauge data, and ultimately productivity. **Fig. 2b** depicts the wellbore, gun, and rock volumes within the experimental chamber.

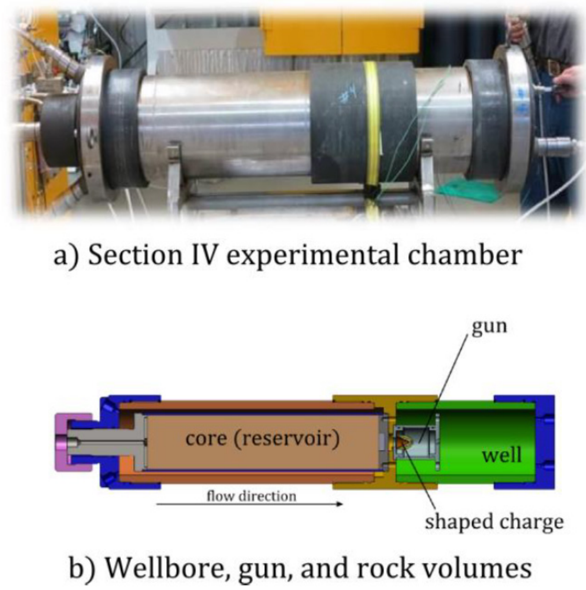


Fig. 2 API-RP 19B Section IV test setup. a) Laboratory chamber, and b) wellbore, gun, and rock volumes inside.

Though the experimental data extracted from these experiments has provided much insight into the perforating process, there are a number of reasons why it was necessary to develop the fast computational model. First, without a theoretical model, experimental data analysis and interpretation for detailed job design are challenging. A theoretical description of the data helps in planning and optimizing experiments, as well as performing design parameter sensitivity studies. Frequently, a proper job design requires a rather large experimental matrix, driving high costs. A theoretical model can be used to reduce the size of meaningful design-of-experiments that drives down laboratory costs.

There is, of course, existing software that is capable of simulating the wellbore-tunnel-reservoir system (e.g., see [10] and [11]), but there are limitations in representing the Section IV chamber geometry, and there are too many free parameters unrelated to the flow physics. In addition, the simulation times required to perform design parameter tuning and sensitivity studies are typically too long. The model presented in this paper avoids such problems.

Once developed and benchmarked within the laboratory environment, the fast computational model was tested under field-scale conditions.

DESCRIPTION OF THE MODEL

Consider, for a moment, the diagram in **Fig. 2b** during a Section IV flow test. At the moment the shaped charge detonates, a flow path is created from the reservoir to the well chamber. The geometry of the test fixture indicates that this flow path is complicated. One might be tempted to invoke a complex, fully 3-dimensional numerical approximation of this geometry to predict the pressure transient within the well chamber. However, it should be pointed out that the simplicity of the pressure transient as measured in the well chamber and shown in **Fig. 1** indicates that this is not necessary. In fact, the measurement suggests that a model based on simplified geometry and dominant physics is possible.

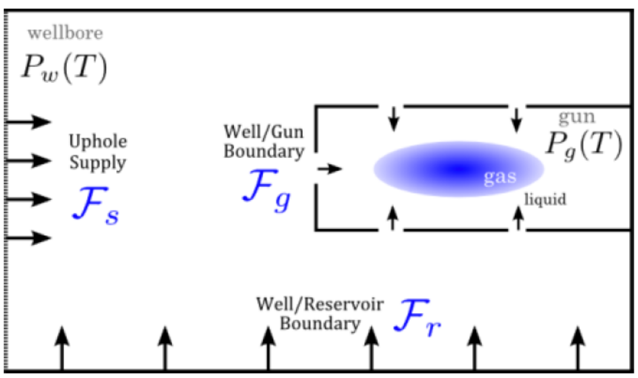


Fig. 3 Simplified downhole geometry

Specifically, the present work has been based on a confined two-phase flow model for which the complex geometry of **Fig. 2b** is mapped onto the simplified geometry of **Fig. 3.** The wellbore is considered to be filled with an incompressible liquid, and the gun with an ideal gas. The flow is described as confined because, away from boundaries, fluid energy is dominated by the potential stored as pressure. **Fig. 3** shows that the mapped geometry is primarily based on volumes and connected areas between the up-hole supply, reservoir, wellbore, and gun. Fluid mass and energy are conserved within the volumes shown, while the conservation of momentum is imposed at the boundaries between volumes. The boundary flux between the uphole supply and wellbore, namely $\mathcal{F}_s$, between the well and gun, $\mathcal{F}_g$, and between the reservoir and well, $\mathcal{F}_r$, transport mass and energy between the reservoir-well-gun system.

Table 1 Dependent variables considered in the model

Variable	Description
$P_w(t)$	Liquid pressure in the well
$P_g(t)$	Gas pressure in the gun
$M_g(t)$	Mass of the gas in the gun
$\vartheta_g(t)$	Temperature of the gas in the gun
$V_g(t)$	Volume of the gas in the gun

Ultimately, the model computes the dynamics of five dependent variables described in Table 1, including the pressure in the well and gun, and the temperature, mass, and occupied volume of the gas within the gun. These dependent variables are ordered into a state vector $\boldsymbol{q}(t)$ such that

$$\boldsymbol{q}(t) = [P_w(t), P_g(t), M_g(t), \vartheta_g(t), V_g(t)]^T,$$

where the superscript indicates a transpose. The dynamical system can then be written as a system of five nonlinear ordinary differential equations in time

$$\frac{d\boldsymbol{q}}{dt} = \boldsymbol{F}(t, \boldsymbol{q}(t); \mathbb{P}),$$

where the right hand side $\boldsymbol{F}$ captures the mass and energy exchange denoted by the interface fluxes in **Fig. 3**. These fluxes, and therefore the right hand side $\boldsymbol{F}$, depend on the set of physical parameters defined by

$$\mathbb{P} = \{L, P_{g0}, P_{w0}, P_p, V_{g0}, V_w, A_g, A_s, A_p, \kappa, \nu, c, \rho, c_p, c_v, U_0, \Psi_0, M_{g0}\vartheta_{g0}\},$$

where L is a length scale associated with the perforation, P_{g0}, P_{w0}, and P_p are the initial pressures within the gun, wellbore, and reservoir, respectively. The FGV is denoted by V_{g0}, the wellbore volume by V_w, and the cross sectional areas connecting the gun, uphole supply, and perforations by A_g, A_s, and A_p, respectively. The formation permeability is denoted by κ, the liquid sound speed by c, and its density by ρ. The ideal gas is characterized by its specific heats c_p and c_v, as well as its initial mass M_{g0} and initial temperature ϑ_{g0}. The last of the physical parameters considered are U_0 and Ψ_0, which characterize velocity and energy scales for the explosive energy source, respectively.

In order to better understand the dominant physics driving the underbalance transient, the time has been scaled by $\tau = V_w/A_g c$, and the dependent variables in **q** by the appropriate parameters in $\mathbb{P}$ In doing so, the dynamics can be captured by a reduced set of seven non-dimensional parameters $\mathbb{N} = \{\epsilon, \epsilon_e, \alpha, a, b, \mathcal{A}, \mathcal{B}\}$, whose relationships to the physical parameters of the model are listed in Table 2. Also listed in Table 2 is a brief description of each parameter's influence over the dynamics.

Table 2 Relationship between the non-dimensional and physical model parameters.

Parameter	Physical Value	Description
ϵ	$\frac{P_{g0}}{P_{w0}}$	Ratio of initial pressure in the gun to the initial pressure in the wellbore
ϵ_e	$\frac{V_{g0}/A_g}{\tau U_0}$	Ratio of length scales defined by gun geometry and the explosives. Typically very small
α	$\frac{c_p}{c_v} - 1$	Reduced ratio of specific heats for the gas within the gun
a	$\frac{A_s}{A_g} + 2\kappa \frac{A_p c}{A_g \upsilon L}$	Influences the rate at which the wellbore pressure drops
b	$\frac{1}{2}\frac{A_s}{A_g}\frac{P_s}{P_{w0}} + \kappa \frac{P_p}{P_{w0}}\frac{A_p c}{A_g \upsilon L}$	Influences the rate at which the wellbore pressure recovers
$\mathcal{A}$	$\frac{\Psi_0}{M_{g0} c_v \vartheta_{g0}}$	Ratio of the explosive to thermal energy within the gun
$\mathcal{B}$	$\frac{V_w P_{w0}}{V_{g0} \rho c^2}$	Influences the rate at which the gas in the gun compresses, and therefore builds gun pressure.

The scaled equations from which these parameters are derived started as a fully coupled physics model for the gun, wellbore, and reservoir. A process utilizing both numerical simulation and analytical approximation techniques was used to simplify the model into the form described above. As indicated by the descriptions in Table 2, the parameters a, b, and $\mathcal{B}$ tend to influence the shape of the wellbore pressure transient most. A detailed study of such influences will be published elsewhere.

The present model requires input defined by the parameter set $\mathbb{P}$, from which the expressions in Table 2 are used to calculate the non-dimensional parameters used to integrate the equations. The output is a time series for each of the dependent variables of the state vector $\boldsymbol{q}$, and listed in Table 1. Typical simulations take less than one second on a modern laptop.

RESULTS AND DISCUSSION

In this section a baseline comparison of the fast computational model with measured test data from an API-RP 19B Section IV test is presented. This is followed with several example simulations in which the wellbore hydrostatic pressure and the FGV are varied to demonstrate how the wellbore pressure transient is influenced. Because an important use case for this model will be at the field scale, its performance is then evaluated against an industry standard and field tested software on an actual field case. Finally, it is shown how the present model can be used in conjunction with existing cleanup models to provide insight into the choice of job design parameters

SECTION IV COMPARISON

It was previously mentioned that the present model depends only on seven non-dimensional parameters that capture the dominant physics. This fact, together with the computational speed inherent in this model enables a straightforward optimization to provide a best fit to experimental pressure data generated during a Section IV test. **Fig. 4** shows the result of such an optimization algorithm. The measured pressure transient is shown in solid magenta, while the calculated pressure is shown as blue dots. As is clear from the plot, the resulting fit is good. We point out that there has been no parameter adjusting, and all optimum parameters result in physically relevant values. Once the non-dimensional parameters that give the best fit are determined, the influence of the physical parameters $\mathbb{P}$ on the DUB transient can be inferred through the dependencies listed in Table 2.

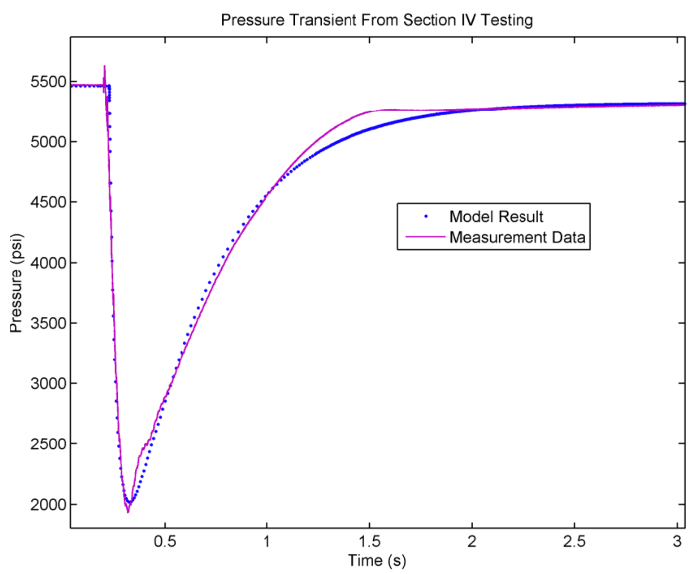


Fig. 4 Comparison of measured (solid magenta) and computed (blue dots) pressure transients during an API-RP 19B Section IV test

PARAMETRIC MODELING IN THE LABORATORY

A powerful use case for this new model is the rapid generation of parametric studies. Beyond generating physical insight into the perforating process, these studies enable better experimental planning and sensitivity analysis on a single design parameter. They have also proven to be helpful in deciphering what may have gone wrong in an undesirable experimental result.

Before discussing an example parametric study, it is important to re-emphasize the value of transient pressure curves as they relate to perforation cleanup. Recall that **Fig. 1** characterizes a DUB pressure curve with the pressure drop ΔP and recovery time τ. It is also likely that there are other characteristics that are important. [4] So regarding "total underbalance management", the cleanup process will be a strong function of these characteristics, so that

$$\textit{clean up} \rightarrow f(\Delta P, \tau, \cdots).$$

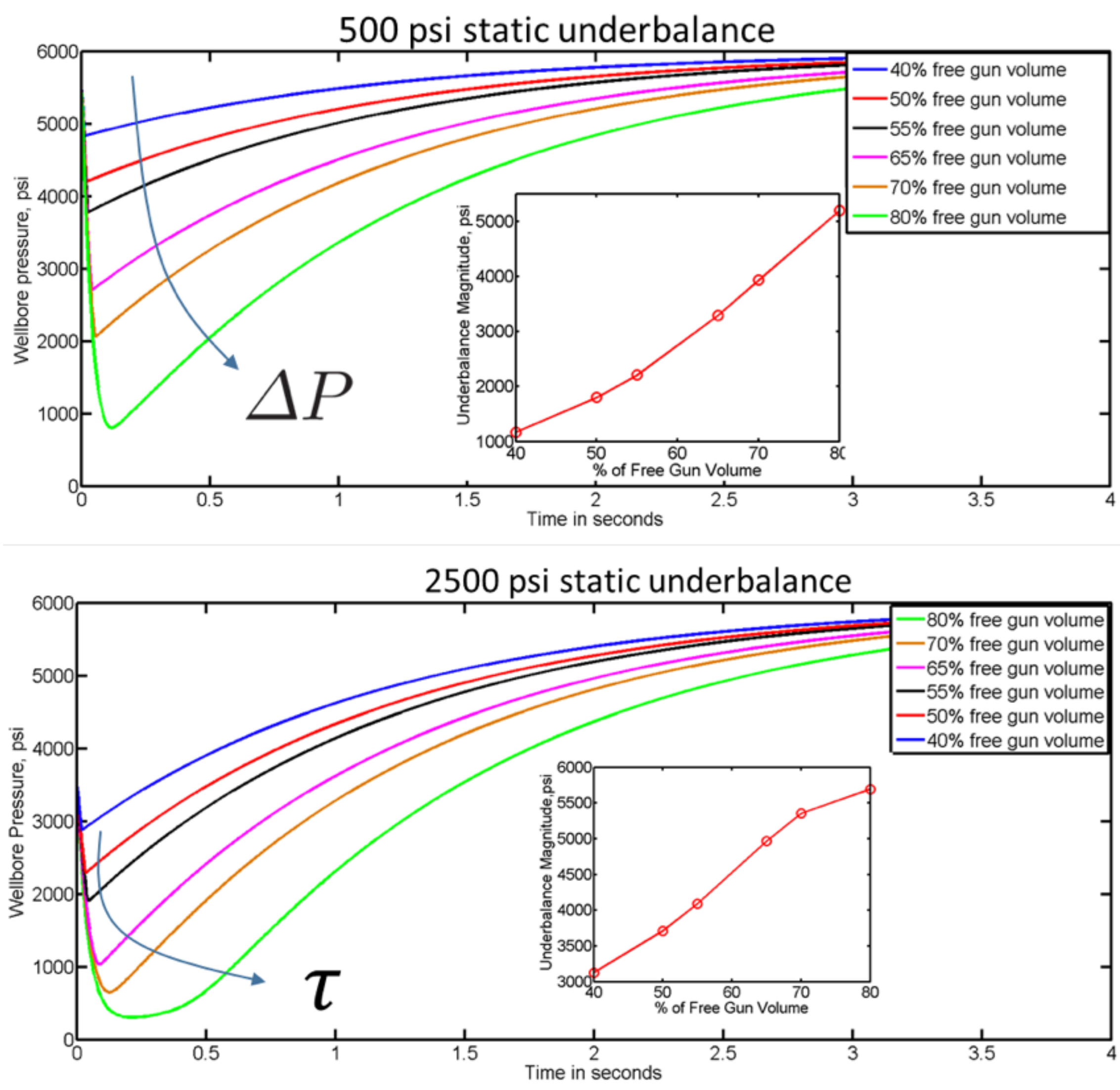


Fig. 5 Transient pressure curves for a varying FGV: at a static underbalance of 500psi (top), and 2500psi (bottom)

Such a function can be used to correlate variants of Carmen-Kozeny or Ergun equations to develop improved perforation tunnel cleanup models. A first step in doing so requires an understanding of the behavior of the pressure curves under different parametric values, and the present model can provide such insight.

To that end, an example parametric study is shown in **Fig. 5** for a 200 mD reservoir with a fixed pore pressure of 6000 psi. Here, the FGV is varied from 40% to 80% at two different values of static underbalance, namely 500psi (well pressure of 5500 psi), and 2500psi (well pressure of 3500 psi). As expected, the dynamic pressure drop ΔP increased significantly with an increasing FGV. This is due to the fact that there is more volume for the wellbore liquid to expand into. This trend is consistent at both static underbalance values. It is interesting to note that at 500psi there was little change in the time that the pressure remained at its minimum value. However, at 2500psi there was a noticeable lengthening of the time at minimum pressure.

This can be understood by the fact that at a higher static underbalance, there was a smaller pressure difference between the well and gun fluids. The result is a lower mass flux across the boundary between the well and gun ($\mathcal{F}_g$ in **Fig. 3**), and therefore a longer time to pressurize the gun. The result is an increasing τ. Such an effect will have strong influence over the tunnel cleanup process.

FIELD SCALE MODELING

So far, the fast computational model presented here has been benchmarked in terms of Section IV testing. In fact, there is nothing in the model derivation that limits its application to laboratory scale volumes, flow rates, and other physical parameters that go into its non-dimensional description (i.e., see the set $\mathbb{P}$). This is one of the powerful consequences of the geometric simplification shown in **Fig. 3**. This means that up-scaling this model to a field scale is a matter of recalculating the non-dimensional set of parameters $\mathbb{N}$ in terms of the relevant physical parameters for the job.

As an example of this, consider a field case in which the formation has 25% porosity and 800 mD permeability. This particular job used **9⅝-in.** casing with a 7-in. gun system with 12 shots per foot and 60° phasing. The FGV was systematically increased by placing a blank chamber below the gun. The blank had a fixed diameter of 5.9-in., but the length was set to 10ft, 20ft, and finally 30ft (indicated by an increasing parameter $\mathcal{B}_0$). **Fig. 6a** shows this setup in an industry standard and field tested software. The plots in **Fig. 6** show the pressure within the gun normalized by the hydrostatic pressure in the well, and as a function of time for all three lengths. **Fig. 6b** shows the gun pressure as calculated by industry standard software, and **Fig. 6c** shows the same pressure as calculated by our fast computational model. In both cases the time has been normalized by $\tau = V_w / A_g c$. Though there are small differences in the details, the gun pressure values and timing compares well between the two methods. However, there is a very large discrepancy in the computational time. The industry standard software took about 90 minutes on a desktop computer, while the fast computational model required less than a second for all three lengths.

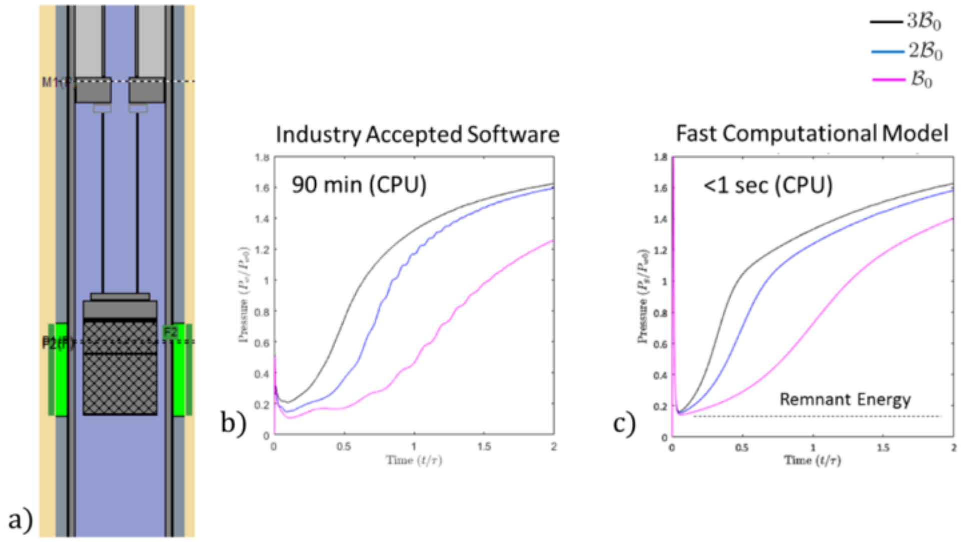


Fig. 6 A comparison of internal gun pressure for a field-scale study in which the FGV is increased by a blank chamber below the gun. Three lengths were used, namely 10ft, 20ft, and 30ft

CONNECTING CLEANUP TO JOB DESIGN PARAMETERS

Since the perforation cleanup mechanism ultimately drives increased well productivity rather than the pressure underbalance itself, the connection made by the present model between practical job design parameters and the cleanup process is perhaps more important than its computational efficiency. In fact, this connection is quite general and can be used to explore a wide range of cleanup models, both static and dynamic.

As an example of such a connection, consider Tariq's well known estimate of the minimum pressure underbalance necessary to achieve cleanup, [6] (Eq. 18)

$$\Delta P = \frac{3.089\times10^{6}\mu^{2}R_e r_2}{\kappa^{0.4}\rho}\left[ln\frac{r_2}{r_1} + R_e r_2\left(\frac{1}{r_1} - \frac{1}{r_2}\right)\right],$$

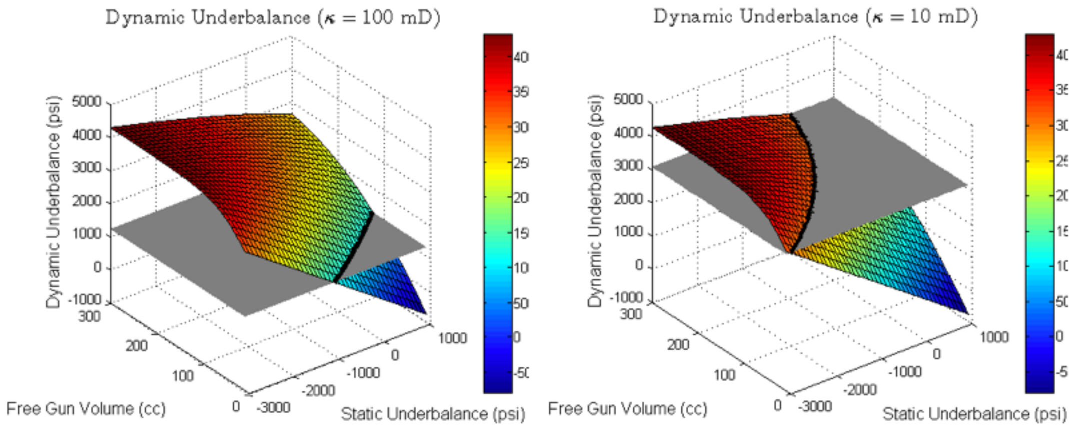
where μ is the oil viscosity, R_e the Reynolds number, r_1 the radius of the perforation, r_2 the radius of the crushed zone, ρ the oil density, and κ the reservoir permeability. Note that for the present model it is straight forward to compute the dynamic underbalance, calculated as follows:

$$\Delta P = \left\|P_p - P_w(t)\right\|_{max},$$

where P_p the formation pressure, and $P_w(t)$ is the wellbore pressure transient output from the present model. This dynamic underbalance can be computed at any number of design input parameters and compared directly with Tariq's estimate. **Fig. 7** shows the result of such a comparison at two different values of the formation permeability, namely $\kappa = 100\ \mathrm{mD}$in **Fig. 7a**, and $\kappa = 10\ \mathrm{mD}$ in **Fig. 7b**, and a fixed pore pressure of 6000 psi.

ARTICLE II

ADVANCES IN COMPUTATIONAL MODELING FOR UNDERBALANCED PERFORATING: FROM LAB TO FIELD



(a) (b)

Fig. 7 Intersection of predicted dynamic underbalance with minimum predicted by Tariq's cleanup model.

The colored surface represents the dynamic underbalance calculated using the present model over a range of free gun volumes (10-300 cc), and static underbalance values (-3000 to 1000 psi). The gray plane represents the minimum necessary pressure differential for successful cleanup calculated using Tariq's estimate based on values used in Ref. [6]. According to this simple example, dynamic underbalance above the gray plane will provide a successful cleanup. It is interesting to note that in both cases only a subset of FGVs and static underbalance conditions is able to achieve successful cleanup. Further, as the permeability goes down, the subset of desired design parameters gets significantly smaller. This is mainly due to the fact that the dynamic underbalance is only slightly effected by the permeability, but the fluid velocity through the tunnel walls is lowered substantially, reducing its ability to clean the tunnel.

The intersection of the dynamic underbalance surface with Tariq's plane in **Fig. 7,** therefore, can be thought of as a design rule resulting from the connection of the present model and Tariq's cleanup model. Future studies will explore in detail such connections with other cleanup models.

CONCLUSIONS

In this paper a fast computational model to compute DUB pressure transients for which the inputs are the relevant physical parameters characterizing the reservoir, gun system, and wellbore geometry has been presented. The model was derived and subsequently benchmarked against high-speed gauge data measured during API-RP 19B Section IV testing. The model was also compared to industry-standard software to demonstrate scalability to the field. Computed pressure profiles have illustrated the combined effects of static and dynamic underbalance on characteristics that have strong influence over the cleanup process. Finally, an example connecting the present model to a well-known cleanup model demonstrates how the present model can be used to develop and analyze perforating job design rules.

In future work we aim to use this model to develop better perforation tunnel cleanup predictions that depend, not only on surge flow or pressure gradients, but directly on job design parameters. More generally, this fast computational model also provides a foundation upon which one can explore sand failure mechanisms, production flow analysis, and optimize perforated completions.

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